Prerequisites of high power charging infrastructure and fully electrical machinery implementation in harbor environment

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ABSTRACT OF THE
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Tightening environmental requirements and cheaper operating costs have led to replacing diesel machinery with electrical drives. Common challenges in machinery electrification is the dependency on the close proximity of electric supply, and low energy density and high prices of batteries.

This master's thesis studies the prerequisites of implementing high power charging infrastructure and electrical machinery in harbor environment. For this thesis, two qualitative interviews were conducted to form a comprehension about harbor environments and operations. Additionally, certain factors - such as available charging power and time - that affect the implementation of electrical powertrains, were understood better.

Using these interviews, generic models of harbor operations were developed to assess the impact of the factors. Using design criteria, that include machinery power, operating time, yearly operating hours, battery energy content, and cycle duration, two total cost of ownership models were created for baseline cases of opportunity and depot charging concepts, and the results were compared to the cost of similar diesel machinery. The effect of the design criteria to the total cost - with other factors such as battery and infrastructure cost - was studied using sensitivity analysis, while recognizing key cost factors.

Based on the models, it was found that opportunity charging is a technically feasible method to implement in harbors, while being financially profitable. The key factors for the opportunity charging concept are yearly usage, fleet size, and electricity price. The key factors for the depot charging concept are the unit cost of kWh for batteries, and battery lifetime. There is more uncertainty about the feasibility of the depot charging concept due to the large size and high cost of the battery. Also the total cost of ownership of the concept is very close to that of the diesel machinery.

Keywords: Charging, Container, Electric drive, Electrification, Harbor, Infrastructure, Operations, Port, TCO, Work cycle

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Kiristyvät ympäristövaatimukset ja edullisemmat käyttökustannukset ovat johtaneet dieseltyökoneiden korvaamiseen sähköisillä. Sähköistyksen yleisenä haasteena ovat riippuvuus sähkönsyötön lähesyydestä, akkujen matalat energiatiheydet sekä korkeat hinnat.

Tämä diplomityö tutkii sähköisten työkoneiden ja vaadittavan latausinfrastruktuurin käyttöönoton edellytyksiä satamaympäristössä. Työtä varten tehtiin kaksi kvalitatiivista haastattelua satamaympäristöjen ja -toiminnan syvemmäksi ymmärtämiseksi. Lisäksi, tiettyjä tekijöitä, kuten saatavilla olevaa lataustehoa ja -aikaa - jotka vaikuttavat sähköisten voimalinjojen käyttöönottoon - ymmärrettiin paremmin.

Haastatteluiden perusteella voitiin muodostaa geneerisiä malleja satamatoiminnasta näiden tekijöiden vaikutuksen arvioimiseksi. Suunnittelukriteerejä, kuten työkonetehoa, operointiaikaa, vuosittaisia käyttötunteja, akun energiamäärää ja syklikestoa, käyttämällä luotiin kaksi elinkaarikustannusmallia taukolataus- ja varikkolatauskonseptien perusskenaarioille. Tuloksia vertailtiin samankaltaisen dieseltyökoneen kustannuksiin. Akku- ja infrastruktuurikustannuksen lisäksi, suunnittelukriteerien vaikutusta kustannuksiin tutkittiin käyttämällä herkkyysanalyysiä, ja samalla paljastamalla avainkustannustekijät.

Mallien perusteella huomattiin, että taukolataus on teknisesti toteuttamiskelpoinen metodi satamiin ollen samalla taloudellisesti kannattava. Avaintekijöitä taukolataukselle ovat vuotuiset käyttötunnit, laivuekoko ja sähkön hinta. Avaintekijät varikkolataukselle ovat akkukilowattitunnin kustannus ja akun elinikä. Varikkolatauskonseptin käyttökelpoisuuteen liittyy enemmän epävarmuutta, sillä siinä akut ovat suuria ja kalliita. Myös konseptin elinkaarikustannus on lähellä dieselin vastaavaa kustannusta.

Avainsanat: Kontti, Lataus, Infrastruktuuri, Kokonaiskustannus, Operaatio, Satama, Sähköistys, Sähkökäyttö, Työkone, Työsykli

Preface

This thesis was written at VTT Technical Research Centre of Finland as a part of a project Electric Commercial Vehicles (ECV) workpackage *eCharge*, which concentrates on studying charging infrastructure and power grid of heavy-duty electric vehicles. The project is running between 2012–2016 and is funded by Tekes – The Finnish Funding Agency for Technology and Innovation.

I want to thank my supervisor professor Marko Hinkkanen and instructor Samu Kukkonen for their guidance and effort during this research and writing process. Special thanks to Juho Leskinen (R&D Engineer at Kalmar, Cargotec), and Jukka Kallio (Director at Vuosaari Port), who agreed to be interviewed, and answered a lot of operations-related questions about harbors. The interviews gave a great insight into harbor operations and helped to gain perspective from the viewpoints of equipment manufacturer and harbor department.

Espoo, 28.9.2015

Teemu Raitaluoto

Contents

Symbols, abbreviations, and terms

Symbols

Ah	Ampere-hour, capacity
C	C-rate
Wh	Watt-hour, energy
Wh/kg, Wh/l	Energy density
W/kg, W/l	Power density

Abbreviations

ASC	Automatic stacking crane
BEV	Battery electric vehicle
BMS	Battery management system
CO	Carbon monoxide
CO_x	Carbon oxide
DPM	Diesel particulate matter
ECV	Electric commercial vehicle
EV	Electric vehicle
GEV	Grid-operated electric vehicle
HEV	Hybrid electric vehicle
LFP	Lithium iron phosphate ($LiFePO_4$)
LHD	Load haul dump
LTO	Lithium-titanate ($Li_4Ti_5O_{12}$)
NO_x	Nitrogen oxides
NRMM	Non-road mobile machinery
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
RTG	Rubber-tired gantry
SO_x	Sulphur oxides
STS	Ship-to-shore
TCO	Total cost of ownership
TEU	Twenty-foot equivalent units

Terms

Bulk	Unpacked cargo, for example: coal.
Cycle duration	Sum of operating and charging durations.
Depot charging	Overnight charging at warehouse location.
Dock, pier	The location to anchor a ship at harbor.
Dock operator	In charge of cargo loading and unloading.
Electrical drive	Converts electrical energy to mechanical energy using power electronics and electric motor.
Feeder port	Port that distributes to smaller ports.
Harbor	Waterside, container yard and landside.
Housekeeping	To arrange containers for easier access.
Hub	Large port that acts as central for other port activities.
Lo-lo ship	Lift-on/lift-off ship.
Opportunity charging	Utilizing a break in operating cycle for charging.
Port	Harbor excluding the waterside.
Quayside	Area, where the quay or ship-to-shore cranes operate.
Ro-ro ship	Roll-on/roll-off ship.
Ropax	Roll-in/passenger ship.
Shipper	Offers shipping services.
Spreader	Attaching part of a crane, spread for different widths.
Storage area	Warehouse building, storage field or container yard
Storo	Stowable roll-in/roll-out ship
Total cost of ownership	Accounts all lifetime costs of an investment.
Transfer area	Area, where container exchange takes place.
Yard	Container storage area.

1 Introduction

1.1 Background

The inspiration and research need for this thesis arose from current studies of public city bus transport electrification. In this thesis, the feasibility analysis methods are now applied to harbors. In Finland, the bus electrification has been studied by VTT in eBus, eBusSystem, and eCharge projects since 2012 in addition to research carried out by selected universities. In a larger perspective, the increasing concern for environment and health aspects has led to the study of alternative solutions for traditional diesel engines and vehicles. This would also decrease the companies' dependency on world's fossil fuel reserves as other methods can be used to produce the electricity that is needed to operate electrical drives. Additionally, legislation and environmental goals already steer development towards greener technology and away from global warming. A financial incentive for companies to use electric drives stems from lower operating costs.

Although diesel engines offer longer operating range and higher autonomy than battery-operated electric drives, the benefits of electric drives and disadvantages of diesel machinery should not be ignored. These benefits include lower operating temperatures, decreased maintenance costs, decreased fuel consumption, decreased pollutant emission, and better and safer working conditions. [1]

Diesel engines emit pollutants such as diesel particulate matter (DPM), carbon oxides (CO_x) and nitrogen oxides (NO_x), which are harmful to people and the environment. Especially DPM exposure has been shown to increase risk of lung cancer among mining workers. Carbon oxides can cause poisoning or immediate death, if a person is exposed to too high concentrations for too long. Another safety hazard, that affects personnel operating diesel machinery, is the louder noise levels, which can lead to an impaired hearing. Local emissions in electrical machinery are non-existent and the operation is quieter, which can lead to longer careers. [1]

In addition to environmental and health concerns, one of the main drivers of interest towards electric machinery are the lower operating and maintenance costs, which should offset the often higher initial investment costs in order to be considered profitable investments. With the increasing wealth and standard of living of emerging economies, the demand for crude oil is bound to increasing the operating costs of diesel machinery and making electrical solutions more attractive.

1.2 Purpose and scope

This thesis studies the feasibility and requirements of electrical machinery in harbor environments in order to decrease the current dependency on fossil fuels and to decrease the harbor operating costs. The purpose is also to contribute to the development and introduction of electrical drives in industrial applications. As the harbor industry is generally a competitive industry, this thesis expands the science community's knowledge in that field as well.

This thesis aims to compare the hourly cost of using electrical drives to that of diesel machinery, and to determine the key factors, that create most uncertainty in the estimates. The findings are used to steer future studies in the direction that can contribute the most to the generalization of electrical machinery.

In order to comprehend the harbor environment to a further extent, two qualitative interviews were conducted. The first interview took place at Tampere, Finland with Juho Leskinen, a research and development engineer at Kalmar, Cargotec. Kalmar is a worldwide manufacturer of cargo handling solutions. The second interview was conducted with Pekka Hellström, a development manager at Vuosaari Port, Helsinki, Finland. Vuosaari Port has an important role in Finnish foreign trade.

Feasibility analyses of different charging concepts are done using two generic operations models to find and compare key variables and limitations of different concept. The main concepts studied in this thesis utilize opportunity and depot charging. The requirements and implementation are analyzed so that it is easier for harbors to introduce electrical drives and charging infrastructure into their existing operations, while also informing container handling equipment manufacturers of the necessary requirements set by electrical machinery.

Based on the findings of the technical feasibility analysis, economic feasibility is studied as well. The total cost of ownership (TCO) of electrical drives is compared to that of diesel to determine the most cost-competitive concept. The results are presented on a cost per hour basis to achieve easy comparability. The TCO calculations take into account all the costs, that are created during the lifetime of an investment. However, some costs are impossible to include due to a small number of available sources.

All of the factors in the techno-economic feasibility analysis are changing variables in the long run, which is why sensitivity analyses will be performed. Using the sensitivity analyses, the key variables that have the greatest effect on the TCOs can be determined. Based on the results, suggestions about the feasibility of machinery electrification and most suitable machinery type for electrification will be made. In assessing profitability of different investments, the effect of diesel price is particularly interesting, because it is affected by political factors, carbon taxes, and country [1]. Between 2014 and 2015 the world economy has experienced a significant decrease in oil price, which greatly affects the feasibility of diesel machinery.

In harbor environments, the operating conditions may vary greatly, which makes generalization of results challenging. It should be noted that every harbor requires individual analysis and operations planning to achieve optimal design. Another challenge of this thesis is the lack of publicly available sources.

This particular industry is studied, because Finland is strongly dependent on harbor activity due to geographical location and exports-dependent economy. There has also been interest towards this kind of study from local companies. The methods of this thesis could be later applied to other environments, such as mining and forest industries, that have traditionally been users of diesel and diesel-hybrid vehicles and machinery.

1.3 Contents of the thesis

Chapter 2 introduces basic harbor environments, their significance to foreign trade, the terms and definitions that are used in harbor operation. The chapter also includes descriptions of different harbor types and stakeholders at the harbor site. In addition to general aspects, the chapter outlines the most common container handling equipment, their tasks, and work cycles. This information is later used in chapter 4.

Chapter 3 covers the topic of electrical machinery. The motivation to use electrical machinery in harbor environments is explained and different topologies are described with their benefits and disadvantages. Particular interest is in battery electric vehicles (BEV) and high power charging technologies as they do not yet have an established presence in the industry.

In chapter 4, the technical feasibility and TCO models are developed and hourly costs of different electrical charging concepts are compared to those of diesel machinery. Because some of the model variables are flexible in the long run, sensitivity analysis is performed to find the key varibles that affect the TCO the most. Based on the results, suggestions about the most feasible machinery for electrification are made. Limitations of the models are considered shortly for further development and application of the models.

Chapter 5 concludes the thesis, discusses the results and the topic in general. Also, further study is encouraged to make more advances in this field and to add to the knowledge of this subject.

2 Harbor environment

2.1 General aspects of harbor environments

This section introduces some general aspects of harbor environment such as definitions, role in foreign trade, different harbor types, and stakeholders. This offers the reader some insight into an industry that is generally very poorly known to outsiders.

2.1.1 Definitions and terms

Sailing ships and engaging in harbor activities is a very old profession, which is why it has its own special vocabulary and established definitions. This chapter discusses the basics of harbor activitity.

The definition of a harbor is vague, and different definitions include different activities. In its most widest form, a harbor consists of the near land and sea areas, where infrastructure and services are arranged by different organizations. In this definition the harbor is an entity, which provides cargo and passenger transportation services, and where other stakeholders participate in service production as well. Other definitions specify a harbor as a physical area, which includes harbor areas, yards, docks, and land and sea transportation routes. This definition can be enlarged to include buildings and machinery of the harbor. [2]

The reasons for arranging harbor activity are manifold. The most basic function of a modern harbor is to act as a distribution center, in which cargo and passengers are loaded and unloaded. [3] A harbor is the point in transportation chain, in which cargo and passengers change from land to sea transportation and vice versa. Harbors also provide storage services for later distribution. [2] Other purposes for harbors and its areas include ship building, repairing, and supplying. Additionally, harbors act as storm shelters, seafaring, currents and ice movements. [3]

A port facility or port is the area of immediate interaction, that takes place between a ship and a harbor. One harbor can include multiple ports and it also consists of the anchoring areas, waiting areas and the entrance routes. [2] The port is the main area for cargo loading and unloading, and it is commanded by the International Maritime Organization (IMO) and the its International Code for the Security of Ships and Port Facilities (ISPS). [3] At the port, a ship is secured to a berth.

A generic map of a harbor is presented in figure 1 to visualize and clarify harbor environments. The arragements in the harbor can vary widely as harbor design depends on geographical formation of the land and size of the harbor.

In the figure, the most relevant aspects are the locations of ships, container handling equipment, storage yards, exchange areas, railways, and land transportation routes. The railway is especially interesting, because cargo can be moved straight between a train and a ship due to their close proximity.

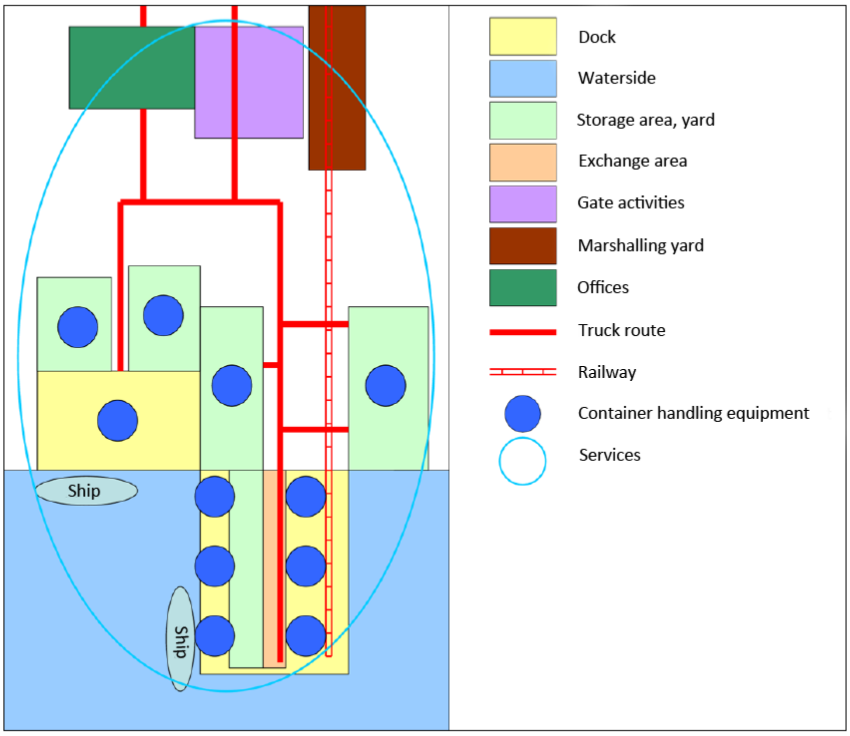

Figure 1: Generic map of a harbor, modified. [3]

2.1.2 Harbor types

There are several different ways to categorize harbors in order to serve different purposes when talking about harbors. The categorization can be done according to

- Product or material flows
- Clientele
- Ownership
- Physical location
- Direction of the material flow
- Usage purpose.

Additionally, there are harbors, in which the ship can be freed from clearing through the customs. [2, 3, 4]

Product and material flows can be further divided into unit good harbors, container harbors, oil harbors, bulk harbors, passenger-car ferry harbors, special harbors, etc. Although the cargo can be mixed sort, the logic is that the most transported product or material defines the harbor type. [2, 3] The container harbors can be further divided into hub, feeder, and trans-shipment harbors. Hubs act as centers of container distribution and the largest container ships usually move between these hubs. The containers are shipped to the hub from smaller trans-shipment harbors and to the trans-shipment harbor from an even smaller feeder harbor. Finnish container harbors are typically these types of feeder harbors, that feed the trans-shipment harbors in Germany and Benelux countries. [3, 5] Feeder shipments can carry between 250–600 TEU (twenty-foot equivalent unit) and hub shipments around 12,000–30,000 TEU [5, 6]. These container harbor categories are the most relevant in respect of this thesis.

The clientele of a harbor can compose of local industries or center points of demand such as cities or towns. [4] This categorization is more rare than the rest.

Division by ownership means that harbors are divided into public and industrial harbors. Industrial harbors are private and owned by companies, while public harbors are owned by the local municipality. [2, 3]

Categorizing harbors by their physical location gives a hint about the accessability of the harbor. The categories are sea, river, canal, and freshwater harbors. These harbors can be built along the natural formations of the land or by constructing the harbor artificially. [3]

Categorization of harbors by the direction of product or material flow divides the harbors into import and export harbors. Usually harbors work in both directions, but the categorization is done by the majority. [2, 3]

Harbors can also be divided by their usage purpose into trade, passenger, war, and boat harbors, etc. [3] This very intuitive and commonplace among people.

2.1.3 Stakeholders

At the harbor site there are a lot of different parties, that are responsible for different tasks [3]. A figure of different stakeholders and their role in the harbor is presented in figure 2.

Governing the whole harbor is the responsibility of harbor department, for example the Port of Helsinki is responsible for an efficient port infrastructure, mainly docks, storage areas, telecommunications, and railway and highway connections. This includes the necessary infrastructure for fueling container handling equipment. [7, 8] The harbor department is also responsible for making contracts with other service providers at the site. Contracts with dock operators are usually 10–30 years long. [8] The harbor departments in Finland aim to function profitably and hence do not use public funds [3].

Consigner is the party, that requires a ship transportation service and contacts a shipper, that makes a contract with a shipping company or a carrier. A shipper delivers the cargo to a ship at the departure port and delivers the cargo to a consignee at the destination port. Depending on agreement, the owner of the cargo during the process can be either the consigner or the consignee. [3, 6]

Shipping companies own the ships, that transport cargo. They pay for the usage of the port and its services. In order for shipping companies to operate as cost-efficiently as possible, visits to harbors must be as short as possible, while costs

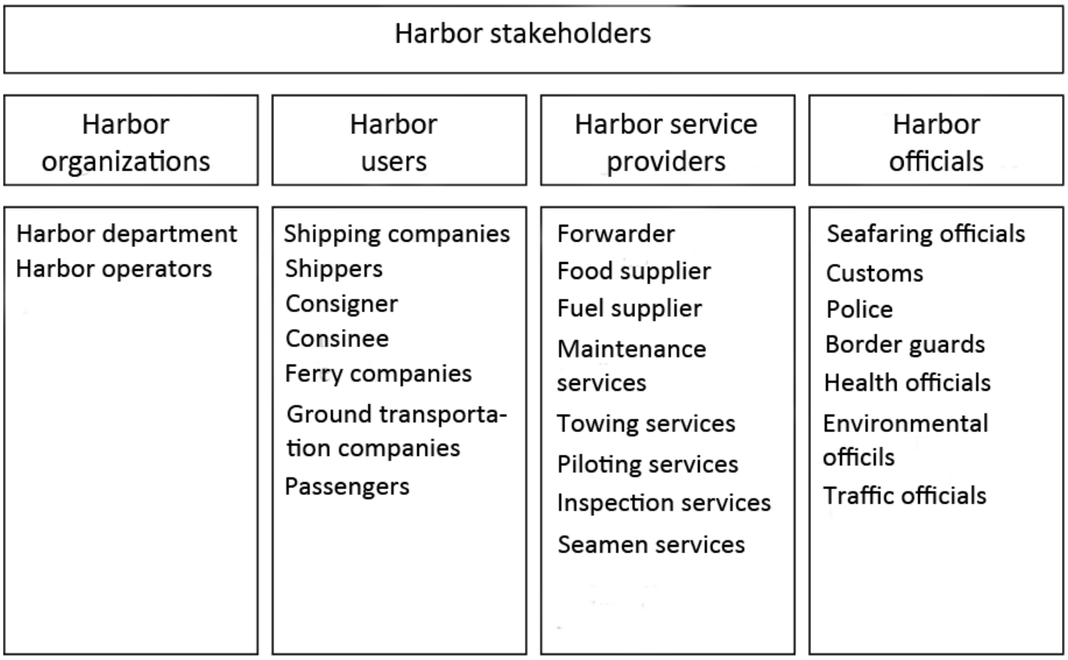

Figure 2: Stakeholders of harbor, modified [3].

should remain low. Shipping companies can reduce costs by inviting tender offers from dock operators, if there are multiple operators available at a harbor. [3, 5, 8]

Dock operators are responsible for loading and unloading cargo at quays as well as handling cargo at storage areas. Dock operators make the final investment decisions about cargo handling machinery, and they are also the owners of the equipment. [8]

There are three ways for dock operators to select greener technology in container handling machinery. Firstly, the pressure could come directly from the harbor department, which could favor green technology when contracting the dock operators. Secondly, the pressure could come indirectly from shippers, that choose the shipping companies, that choose dock operators for cargo handling. And thirdly, dock operators might choose electrical machinery based on better total cost of ownership, enhanced brand image, or emission regulations. [8]

Building charging infrastructure for the electrical machinery requires initial investment. Ownership of the charging infrastructure could belong to the harbor department, which is already responsible for the fueling infrastructure and its development. [5, 8] If the infrastructure were in the harbor department's ownership, the use of the infrastructure could be based on renting or billing [8]. However, it is the dock operator that makes the investment to the machinery, so it would be natural for them to have the ownership [5]. Having multiple dock operators at the harbor - like in case of Vuosaari Port there are three different operators - makes the ownership issue even more complex. Dividing the initial investment cost between different operators could be wise, but it is not seen as a viable option as dock operators are each others competitors, and they often operate at different designated areas. Usually the operators are contracted for several decades at a time, which means that they can safely make long-term investments. [8]

2.1.4 Foreign trade

Harbors have many factors, that affect the total cost of transportation, but are usually necessary for conducting business in the surrounding economy [3]. The operation in harbors should be improved continuously to ensure lower costs, which could result in increased imports and exports growing the global economy.

In Finland, harbor activities are in a key role when it comes to foreign trade as Finland's west border is mostly surrounded by the Gulf of Bothnia and the south border by the Gulf of Finland. This is one of the reasons why Finland is so dependent on sea transportation. Of the value of Finland's foreign trade, 70% of imports and 90% of exports are transported by sea. [6] If measured by weight, 80% of imports and 88% of exports are transported by ship [9].

Structures of Finland's foreign trade are presented in tables 1 and 2. Most of the trade takes place within the Euro area followed by other EU countries and non-EU countries of Europe. The largest trading partners according to the value of trade are Russia, Sweden, and Germany. [10]

Table 1: Structure of Finland's imports in 2013. [10]

Type	%
Raw materials	32.9
Energy	23.0
Investment goods	19.4
Non-durable consumer goods	18.2
Durable consumer goods	6.5

Table 2: Structure of Finland's exports in 2013. [10]

Type	%
Basic metal, machine and transportation products	31.6
Chemical products	24.6
Wood and paper products	20.0
Others	12.3
Electrical industrial products	11.4

Because of the world's energy and raw material resource allocation, industrial production and consumption centers are located in different parts of the world. Over 90% of the world's trade tonnes are transported by sea. Globalization and increased transportation efficiency have decreased the impact of geographical distance in world trade. [6]

The portion of manufactured goods in world exports has increased in recent decades reaching 2/3 in 2013. The portion of fuels and mining products was 25%, while agricultural products were only 10% of the total exports. [11] The leadership of world trade is centered around three countries: United States, China, and Germany. The shares of these countries are presented in table 3. The biggest importer is United States, while China holds the place for the biggest exporter. These are also related as China mostly exports to United States. In 2013, 16.7% of China's exports went to United States, while only 15.3% of exports went to Europe. Of the three trade leaders, China's trading is growing most rapidly. [10] Globalization and the amount

Table 3: Structure of the world trade in 2013. [10]

Country	**Imports (%)**	**Exports (%)**
United States	12.3	8.4
China	10.3	11.7
Germany	6.3	7.7

of trade continues to increase, which makes it imperative to lower the environmental impact of trading in order to secure sustainable development.

2.1.5 Other aspects

Harbors in general are very complex in nature. They can be constructed according to geographical formations of the land, or they can be artificially made, which makes each harbor very different to one another. The characteristics of a harbor affects, which vessel types can use the harbor to load and unload cargo. A ship that loads and unloads its cargo from front or back of the ship is called a *ro-ro* ship, as in roll-in/roll-out ship. This type of vessel is suitable for vehicle and other rolling cargo transportation. [12]

Another ship type is called a *lo-lo* ship, as in lift-on/lift-off ship, that docks sideways and is loaded and unloaded by using a crane. This vessel type is used for container and bulk trasportation. Other hybrid types of lo-lo and ro-ro ships exist, but are not covered here. [12]

As environments, harbors are open air areas, that are exposed to weather conditions such as varying temperatures, dust, salt, sand, winds, rain, ice, and storms. The close proximity to water areas also expose harbors to flooding. Exposure to these extreme weather conditions makes proper machinery and infrastructure design mandatory. [5]

2.2 Harbor machinery and work cycles

In this section, the most common harbor machineries are discussed in conjuction with their typical operation methods and cycles. This discussion acts as a basis for a techno-economic feasibility analysis developed later in chapter 4.

Most harbor machinery are used for handling containers. A basic measurement unit for seafare transportation is TEU (twenty-foot equivalent unit), which is the size of a standard container: 20 feet long, 8 feet wide and 8.5 feet high. Container sizes can vary; a 40-foot container equalling to 2 TEU. Other container sizes include a 45-foot and a 10-foot container. There are also special containers for keeping cargo cold or warm, if needed. These containers are hoisted, moved, and carried between waterside and landside using basic harbor machinery. Due to the high revenue nature of harbor activity, moving containers should be done as fast as possible with minimum costs and damage. [5]

A work cycle can be defined as a sequence of activities and movements, which are ideally repeated with little to no variation at all each time the cycle is performed. Work cycles are usually harbor specific due to different layouts and work rhythm. For example the amount of containers, that are loaded and unloaded per hour varies.

Harbor industry requires high productivity, because of the high earning potential. Activities are run around the clock so the time left to charge battery electric drives is scarce. This is why a work cycle analysis is done so that potential natural breaks could be identified and utilized for charging process.

2.2.1 Ship-to-shore crane

A port that is capable of docking lo-lo ships is usually equipped with ship-to-shore cranes (STS crane, also container crane and container handling gantry crane) for loading and unloading the cargo hold. A STS crane is presented in figure 3. The boom of the STS crane reaches over the ship. The bigger the ships are, the bigger the cranes usually are.

Figure 3: Ship-to-shore cranes and a lo-lo ship. [13]

The amount of STS cranes per harbor depends on the size of the ships, that can dock into the harbor, and also on the amount of piers at the harbor. In large Asian harbors, there are typically around 30 to 40 STS cranes. [5]

A crane attaches on top of a container or multiple containers using spreaders, which attach to the corners of the containers using twistlocks. One spreader can typically lift 2 TEU, while the total lifting capacity depends on configuration. A crane is capable of hoisting two 40-foot or four 20-foot containers at once by using two spreaders. The hoisting capacity can be up to 30–70 tonnes depending on configuration. [3, 5]

The crane operation is more accurately illustrated in 4. After the cargo is hoisted from a ship (A to B), a trolley slides along the boom and brings the cargo to the center of the crane (B to C) or to the backreach area (B to D). The crane then lowers the cargo on top of a terminal tractor, an automated guided vehicle or on top of the ground, which acts as a temporary storage area until a shuttle carrier or a straddle carrier fetches the container. [5].

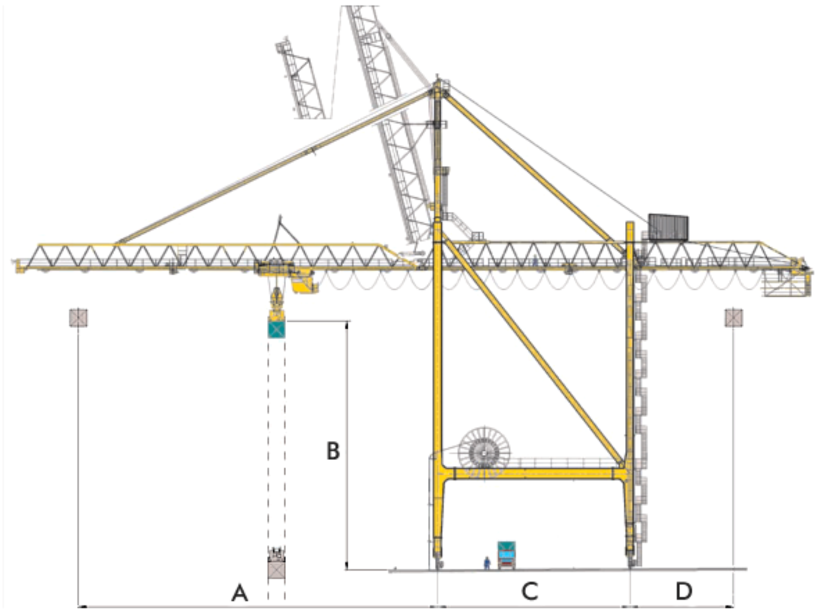

Figure 4: STS schematic, modified. [14]

The cycle time of a STS crane is between 0.5 and 1.5 minutes, which is a limiting factor for the whole loading or unloading operation. A typical speed of operation for a STS crane is around 30–90 moves per hour, while 50 moves per hour is considered an excellent performance. [5]

STS cranes usually work fully on grid electricity without batteries as the cranes are mostly stationary. Some movement along rails is allowed so that all the containers on a ship can be accessed. Currently, STS cranes are mostly manually operated. [5]

2.2.2 Terminal tractor

Terminal tractors work as mediums between STS cranes and the container yard. A terminal tractor is presented in figure 5. The tractor is very small in size, which makes it lightweight and easily accessible compared to a highway truck.

Figure 5: Terminal tractor. [15]

A typical tractor can transport two 20-foot containers or one 40-foot container at a time. The cargo is transported from the crane to the container yard at the containers assigned location or a nearby logistics center, where other machinery unload the cargo. Terminal tractors are additionally capable of loading and unloading ro-ro ships as containers are already on top of trailers and ready to be transported. [5]

For the safety of other stakeholders at a harbor site, the driving speeds of terminal tractors must be limited decreasing its maximum operational productivity. The length between a STS crane and an assigned container location can vary, which makes it difficult to estimate typical cycle times. [5, 8]

Harbor environments are optimized by having as high TEU/hectare -ratio as possible. In order to achieve this, container blocks must be stacked as high as possible, but also as closely as possible. A terminal tractor is capable of sharp turns having a small turning radius making it ideal for narrow space operation. Additionally, compared to a normal truck, attaching a container is faster with a terminal tractor decreasing cycle times. The terminal tractor typically operates on diesel. [5]

2.2.3 Automated guided vehicle

Automated guided vehicles (AGV) shown in figure 6 can work as substitutes for terminal tractors and container carriers, because its work area is also between STS cranes and a container yard. AGV is a platform on wheels and it does not have a cockpit. An AGV waits idle until a STS crane lowers a load on top of it, after which it carries the load to an assigned storage location. AGVs move completely independently using magnetic tracks or other guidance methods, which might make it necessary to restrict the operation area from other machinery and people. A normal AGV cannot lift cargo by itself, so there needs to be a queue of AGVs waiting for cargo from a STS crane in order to avoid bottlenecks from being created. For example, four AGVs could serve one STS crane. An AGV model that is able to lift a container by itself is called a Lift AGV. [5]

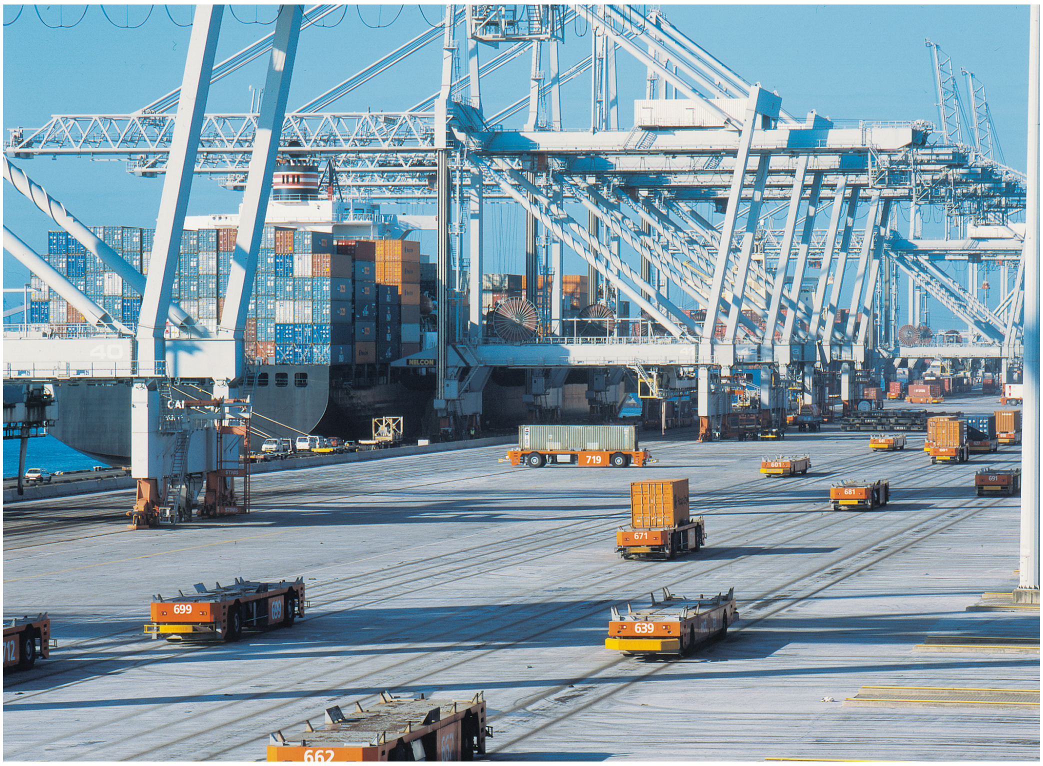

Figure 6: Automated guided vehicle. [16]

AGVs transport containers to transfer areas of container blocks. From the transfer area, containers are lifted by a stacking crane, that is on yard duty. After a container is lifted, the AGV returns to queue for another container near a STS crane. This cycle could take about 5 minutes, from which 1 minute might be idle waiting. AGVs operate mainly on diesel, but solutions utilizing exchangeable lead batteries exist. The latter solution requires a large warehouse for the batteries, which makes it an inconvenient and costly solution. [5]

It is possible for AGVs to misinterpret location information causing them to stray from their tracks and cause damage and delays. AGVs have proximity sensors, which prevent the AGVs from running into other objects, but automated machinery often have their downsides. [5]

The popularity of AGVs in harbors is increasing and there are, for example 300 AGVs used at the port of Rotterdam alone. The AGV can act as a substitute for shuttle carriers - which are discussed next - because it has a similar role in dock operations. [5]

2.2.4 Container carriers

There are two different container carriers: straddle carriers and shuttle carriers. They can be used for different operation, while the design looks similar. Straddle carriers are generally used for piling and arranging containers at a container yard, while shuttle carriers act as mediums between STS cranes and a container yard completing similar tasks to terminal tractors and AGVs. The main difference between the carriers is height. A straddle carrier is usually taller than a shuttle carrier. [5]

A straddle carrier is presented in figure 7. It can lift one 40-foot container or two 20-foot containers simultaneously, which makes it perfect for housekeeping duty or moving containers between storage areas.

Figure 7: Straddle carrier. [17]

From the figure it can be seen that a straddle carrier has most of its equipment, such as a battery and a diesel generator system, located on the top of the carrier. It can also be used in quayside-to-yard duty. The height of a container block can be up to 3–4 containers. The downside to using straddle carriers is, that the space between container rows has to be wide enough to enable the straddle carriers' movements. This can be expensive, because the area of container yards is scarce and expensive. Without straddle carriers, the same process of moving containers between storage areas would require moving several other containers, if the required container were in the middle of the storage area. Additionally, assistance of other container handling equipment equipment would be needed. [5]

A shuttle carrier is a small straddle carrier. It is presented in figure 8. Compared to the figure of a straddle carrier, the smaller size of a shuttle carrier is noticeable. Otherwise the design is similar.

Figure 8: Shuttle carrier. [18]

A shuttle carrier is able to hold one 40-foot container or two 20-foot container similar to a straddle carrier as they often use a similar spreader. A shuttle carrier is only capable of piling one container on top of another, but it is ideal for carrying containers between a STS crane and a container yard, because it can lift a container independently, while other machinery require that the container is lifted for them. This is why a shuttle carrier is estimated to be the norm in the future. [5]

A shuttle carrier can also work automatically like the AGV. These automatic shuttle carriers do not have a cockpit, because a human operator is not needed, which leads to a reduced amount of accidents. In operation, the amount of shuttle carriers needed to service one STS crane is lower than that of AGVs. This is due to the lifting capability of the shuttle carrier. The cycle time for a shuttle carrier is about 5 minutes, of which 0.5–1 minutes might be waiting depending on the layout of the port. Currently, about three shuttle carriers are used to service one STS crane. [5] The rated power of a typical shuttle carrier ranges between 280 and 330 kW and the height is around 10 meters [19, 20].

2.2.5 Stacking cranes

Stacking cranes are used in medium and large ports to handle containers at the storage area. These containers form a container block, where the spaces between containers are kept small, which translates to high utilization of land capacity. The height of a typical container block can be up to six containers. [5]

There are two main types of stacking cranes. The first is automated stacking crane (ASC), which moves on rails and operates independently without a human operator. An ASC is presented in figure 9. There can be multiple ASCs per one container block, which decreases waiting time. Usually, one stacking crane handles the quayside transfer area and the other the landside transfer area. The second carrier is rubber-tired gantry crane (RTG), which operates on rubber wheels. [5]

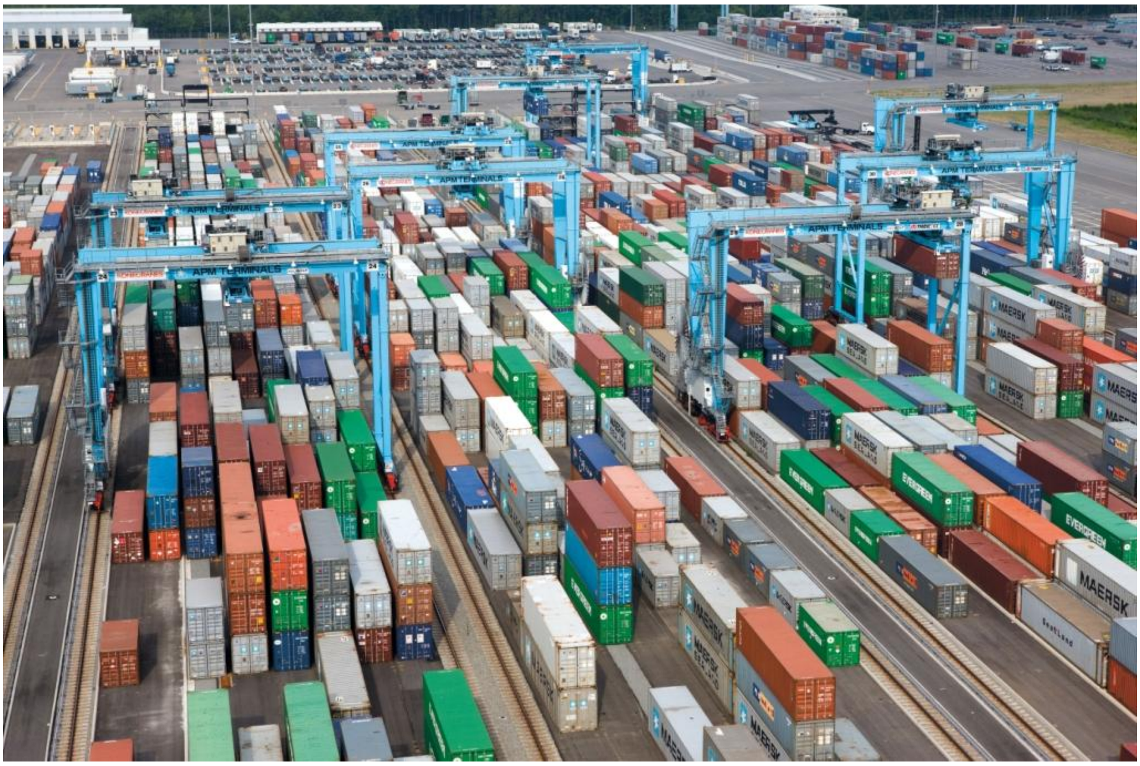

Figure 9: Automated Stacking Crane. [21]

ASCs and RTGs operate on linear paths between the ends of a container block, and their main task is to arrange and stack containers. The quayside transfer area is handled by quayside-to-yard machinery and the landside transfer area by highway trucks. Locations of containers and trucks at the transfer area are measured using lasers, because the cranes need precision in order to operate properly. There are typically multiple spots at the transfer areas so it would not slow down the operation of other machinery. There is also a possibility to use a side lane - that travels along the side of a container block - as a transfer area. This enables the trucks to queue in a line for their turn. [5]

ASCs are always electric and there is no need to use diesel or diesel-hybrid solutions, because the ASCs operate on a linear and predictable path. Electricity is supplied from a cable reel, that also enables movement of the ASC. A downside to using an ASC is, that each container block needs its own crane and a set of rails. Building the rails on an existing harbor might be time consuming and expensive. [5]

Power requirement of an ASC can be several hundrends of kilowatts, meaning that using multiple ASCs might require several megawatts of power. Existing infrastructure and high power requirement are a benefit when implementing other electrical drives to a harbor, because power availability can be guaranteed. ASC is also considered a norm in the future of harbor operations. [5]

RTGs are slightly more flexible to move around the container yard as they do not work on rails, but on rubber wheels as seen from figure 10. A RTG can be moved from one container block to another when necessary, decreasing total investment costs. A downside to using a RTG is, that it requires a human operator, which increases the odds of human error, while it also decreases productivity and incurs labor costs. [5]

Figure 10: RTG crane. [22]

RTGs can operate on diesel or on a diesel-generator setup, but they can also be supplied by an electric rail or a cable reel. The electric rail is usually located next to the container block. Another human-operated stacking crane type, which is not covered here, is called a rail-mounted gantry (RMG). [5]

The market for RTGs is slowly fading as automated harbors are increasing in popularity. In Australia, there are currently several harbors with different levels of automation. Although the Lean Thinking - which advocates inventory reduction and fast movement of goods - is increasing in popularity among businesses, the amount of world trade and transported goods continues to rise rapidly, which makes storing and stacking containers even more necessary than before. [5]

2.2.6 Reach stacker

Reach stackers are mainly used for housekeeping duty in medium ports and for container stacking in smaller ports. Reach stacker attaches a spreader on top of a container and uses hydraulics to lift it. Reach stackers are capable of stacking up to 5 or 6 containers and lifting up to 120 tonnes, while typical capacity is around 45 tonnes. [5] A reach stacker is presented in figure 11, in which a container is lifted hydraulically. An extending boom enables reach stackers to reach high container stacks.

Figure 11: Reach stacker. [23]

Currently, diesel and diesel-hybrid models exist in the market, but fully electric versions are not available yet. Reach stackers are mainly used for their flexibility in short range operation, and because they can lift higher than a forklift truck. In addition to container handling, reach stackers can lift other types of cargo as well, for example steel rolls, by using specialized lifting accessories. Reach stackers can also be used in other industries other than harbor industry, for example in automotive industry they are used in goods receptions to handle containers. [5]

The normal operation of a reach stacker might be unpredictable. It might have to relocate to another part of a container yard several times per day, which makes it difficult to estimate a typical work cycle. [5]

2.2.7 Masted container handler

There are two main types of masted container handlers. The first type is meant for empty containers and it attaches to a container from the front side. The other type is meant for loaded containers and it attaches from the top side. The latter type is also presented in figure 12 to illustrate, that it uses a similar speader to those found in reach stackers and container carriers. A spreader makes it easier to adjust for the length of a container. [5]

Figure 12: Masted container handler. [24]

The difference between the two masted container handlers is the machinery's ability to produce hydraulic force. By using hydraulics, a masted container handler for loaded containers can lift a container on top of four other containers. A masted container handler for empty containers can stack up to nine containers. Currently, diesel or diesel-hybrid models exist. [5]

The operation range of a masted container handler is small. A typical work station is at the container yard, where the machine commences housekeeping duty. In small ports, a masted container handler can store the containers, that a terminal tractor brings. If the next container arrives too slowly, a natural break occurs and the masted container handler has to wait for its next task. The operation is similar to a reach stacker, which makes work cycle estimation difficult. [5]

2.2.8 Forklift truck

Harbors usually need forklift trucks for moving cargo, if the cargo is not in a standard container and needs to be moved short ranges. Examples of these kinds of cargos are paper rolls and metal products like in figure 13. In the figure, metal products are

Figure 13: Forklift truck. [25]

placed on top of a pallet, which is lifted by the forklift. It looks similar to a masted container handler, but the attachment part is different since the movable loads are different.

Forklifts are also suitable for loading and unloading containers. A forklift is perfect for moving objects, that are on top of pallets, which are often used in industrial operations. Currently, the smallest forklifts are electric, while larger loads are handled by diesel forklifts. There are no easily identifiable repetitive patterns in forklift truck operations because of the forklifts' versatility. [5]

3 Electrical machinery and charging technology

Electrical drives can offer a host of benefits compared to diesel engines. The benefits range from cost savings to health benefits. The benefits are discussed more in chapter 3.1.

Electric non-road mobile machinery (NRMM) are categorized in to four groups. The categories are: battery-operated electric vehicles (BEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and grid-operated electric vehicles (GEV). BEVs use batteries, which are used instead of diesel, but they can also be used together in HEV and PHEV solutions. The difference between HEVs and PHEVs is that PHEVs can be charged from a grid supply by using a plug-in cable, while HEVs cannot be charged. What HEVs and PHEVs have in common is that they both have a battery and a diesel engine to provide similar autonomy to diesel machinery. GEVs do not need batteries or diesel engines, since GEVs are constantly connected to grid that supplies .

Since three of the groups mentioned earlier use batteries, battery technology is discussed in chapter 3.2. The chapter discusses two battery types: lithium-titanate $Li_4Ti_5O_{12}$ (LTO) and lithium iron phosphate $LiFePO_4$ (LFP). Both of the battery types have characteristics that are valued in electrical machinery.

The development of charging technologies and standards has been driven by advances in the fields of electric public city transportation buses and electric cars. Chapter 3.3 discusses different charging system categories and standards that relate to electric commercial vehicles (ECV). The charging system categories discussed here are plug-in cable, pantograph, and induction. Each of these technologies have their own unique characteristics that are at an advantage or disadvantage in the harbor environment.

Chapter 3.4 discusses supply technologies suitable for GEVs. The main technologies discussed here are overhead line and rail, and trailing power cable.

3.1 Characteristics and benefits of electrical machinery

There are some fundamental characteristics, that make electrical drives more attractive compared to diesel engines. These characteristics range from cost efficiency to environmental factors, and all of them should be considered instead of only the initial investment costs. With electrical machinery, there are potential cost savings in operating costs, consumables, and maintenance. [1]

Environmental factors that are associated with electrical machinery are efficiency and emissions. Firstly, the efficiency of electricity generation is better in a power plant than in a combustion engine. Secondly, the electricity can be produced using environmentally friendly methods such as hydropower, solarpower, or windpower, which decrease CO_2 emissions per kWh produced. Thirdly, the energy efficiency of an electric motor is superior to that of a diesel engine. And lastly, all the harmful emissions, such as nitrogen oxides (NO_x), particulate matter (PM), and carbon oxides (CO_x), are produced at the power plant. Electrical drives produce zero local emissions, which is better for worker health. [1, 26]

The exhaust of diesel engines requires filtering, which creates additional costs in maintenance, waiting time, and treatment. Cost savings are also created, because electrical machinery does not need lubricant oils for the engine or transmission. Only hydraulic systems and axles of the machinery require such consumables. [1]

Compared to diesel engines, electrical machinery produce less noise when operated, which is particularly useful in harbors, which are located near to cities. The noise reduction is around 20 dB, which also increases personnel health. [1] A diesel engine creates vibrations when operated, which fatigues the body of the machinery. This can translate to shorter machine and chassis lifetimes. [26]

Torque characteristics of electrical machinery outmatch those of diesel engines. Maximum torque is produced even at lower operating speeds, which translate to good acceleration properties increasing productivity. This is particularly useful, if operating cycles at the harbor are discontinuous and abrupt. Electrical motors work more efficiently in this kind of movement, because the motor can regenerate braking energy back to a power supply. The efficiency of regenerative braking and reusing the energy is around 70%. In diesel machines, braking causes additional wear of mechanical parts. [26]

The prices of diesel and electricity differ by country. For electricity, such factors as production method affects the price greatly. There are also additional costs from transmission. The transmission cost is similar to the transportation cost of diesel. In Europe, electricity and diesel are quite expensive, while they are both relatively cheap in the Americas and Asia. [27, 28]

The efficiency of BEVs is found to be approximately 84% in figure 14. This figure accounts losses of electrical drivetrain and batteries. Comparably, one liter of diesel

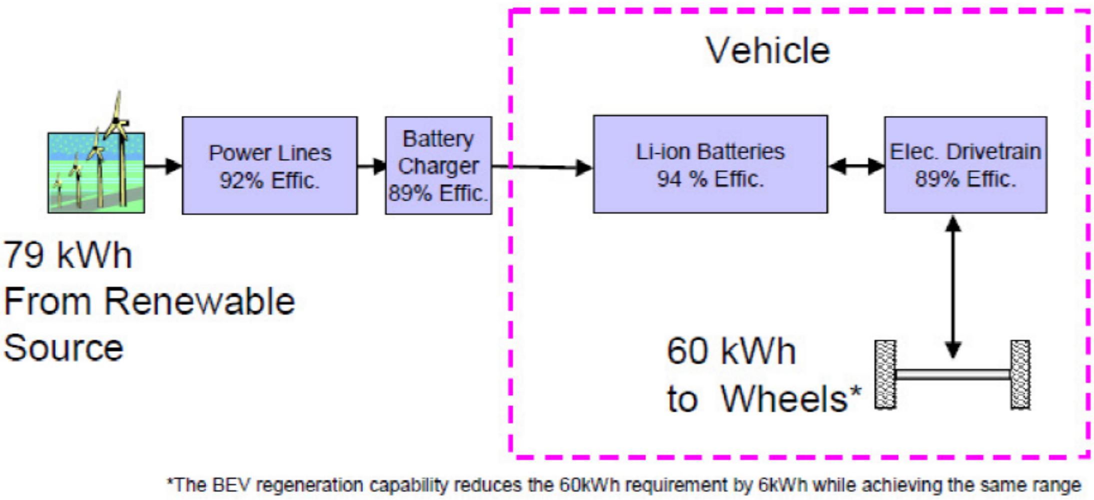

Figure 14: Well-to-wheel efficiency of BEVs [26].

fuel roughly translates to 10–11 kWh of energy, while the conversion efficiency of a diesel engine is only about 40% at best. This means that 1 liter produces 4–4.4 kWh of energy or that 0.227–0.25 liters of diesel is used to produce 1 kWh of useful mechanical energy. [29, 30] Newer diesel-hybrid solutions consume about 30–40% less fuel compared to traditional diesel engines, which is due to the regenerative abilities, diesel engine downsizing, and more optimum operation in the efficiency curve of a diesel engine. [31, 32]

The emission regulations for diesel engines have become stricter since the introduction of Tier 1 standard in 1998. Currently, there are five different Tier standards, latest of which is the Tier 5 standard that is supposed to come into effect in 2019. The purpose of the standards is to prevent premature deaths due to respiratory illnesses. Emission reductions are achieved by implementing advanced exhaust gas after treatment, which in turn increases the price of diesel motors. [33, 34] Such standards do not concern the electrical machinery, although HEVs are an exception, since they have an engine. However, electric motors do have efficiency standards that are becoming stricter in the future. This can increase the price of electrical machinery, but will reduce the operating costs at the same time due to higher efficiency. [35]

3.2 Battery technology

Electrical machinery can be supplied from a battery, which utilizes a chemical process to store and release electrical energy. Batteries make the energy easy to transport and use later. The purpose of a battery is usually to be rechargeable as opposed to being disposable. [36] Only secondary batteries (rechargeable) are discussed in this thesis as disposable primary batteries are not very applicable for electric vehicles.

Batteries can be connected in parallel and series in order to achieve higher power and energy content. The batteries need a battery management system (BMS) for control and protection. [36] A BMS is required for lithium-ion (Li-Ion) based batteries, as it is responsible for numerous tasks such as safety and charging process control [37].

The most important characteristics of a battery include its price, energy content, power capability, safety, energy and power density, and lifetime. The energy content of a battery limits the operating range of a battery-operated machine, while power capability determines the machine's ability to accelerate. For high power charging, charging power capability is also important, because it affects the charging period duration. The charging power can momentarily exceed the allowed limit of continuous charging power capability. [36, 37]

Energy density is usually expressed as Wh/kg and power density in W/kg, but they can also be expressed as Wh/l and W/l, respectively. The densities bring limitations to the acceptable size of a battery. For batteries, the energy and power density properties are somewhat exclusive since thicker inner wiring is needed for higher power, but it leaves less space for energy storing material decreasing energy density. The most promising battery technologies utilize lithium because of its superior energy density. [36, 37]

One of the problems of using batteries in industrial machinery relates to power. The amount of power an industrial machine needs ranges from several kilowatts to a few hundred kilowatts. The large power requirement translates to large battery sizes or the need for power optimized batteries. An electric load haul dump (eLHD) used in mines required 1.5–2 tonnes of batteries and only allowed for 2–2.5 hours of operating time after which the eLHD had to be charged for about 2 hours. [1]

When batteries age, their ability to store energy deteriorates [38]. The loss of capacity is dependent on temperature, discharge and charging power, power profile, and depth of discharge (DoD). DoD indicates how much of the battery's energy content has been discharged. Generally, the shorter the discharge period is, the more discharge cycles the battery can withstand without losing too much of its capacity to store energy. The relation between DoD and cycle count is presented in figure 15 for LFP and LTO battery types. [39] From the graph it is clear that the battery lifetime increases exponentially, when the DoD decreases. When DoD is at 100%, the cycle counts for LTO and LFP are 12,000 and 2,000, respectively. Using a bigger, and therefore usually more expensive, battery allows for a smaller DoD to be used, which increases the lifetime of the battery, if the operating profile and other factors are kept the same. Additionally, a smaller charging and discharging power in relation to the battery's energy content increases lifetime as well. This trade-off between size and lifetime should be further considered when making final design decisions. Another trade-off is that LTO batteries can reach higher cycle count than LFP batteries, but LTOs are almost double as expensive. [40]

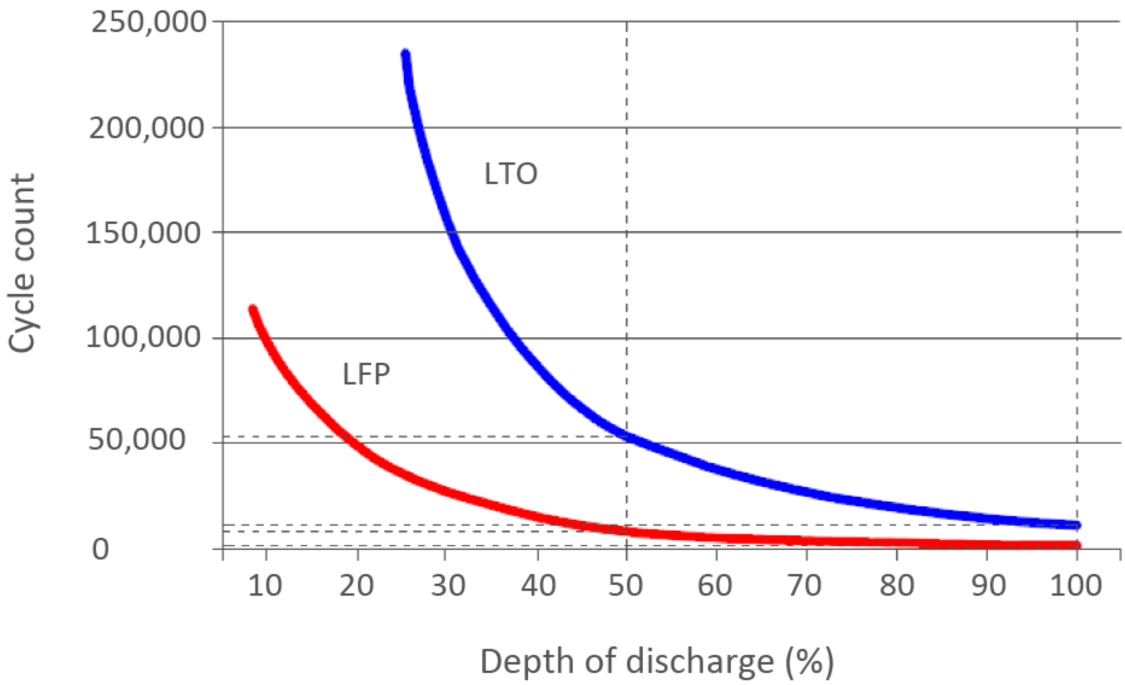

Figure 15: Effect of DoD to the battery cycle count in LFP and LTO batteries, modified [40].

The lifetime is additionally shortened by too high charging currents and wrong operating temperatures. [36, 39] The range of operating temperatures could easily be improved by proper insulation, cooling and heating, which would allow for varying temperatures. In electrical vehicles, batteries are usually one of the most expensive single components, which is why it is important to ensure a long battery lifetime by proper design and operation. This increases the profitability of battery operated machinery. The battery type has a significant effect on the expected lifetime but also on other characteristics of the battery. [41]

Price estimates of Li-Ion batteries for BEVs have declined from over a $1,000/kWh in 2007 to around $410/kWh in 2014, representing a 14% annual decline. The leading manufacturers of BEVs have reportedly used battery packs, that cost around $300/kWh, with an annual decline of 8%. Prices are expected to reach around $230/kWh in 2017–2018, $200/kWh in 2020, and $160/kWh in 2025. The batteries used in BEVs are energy optimized rather than power optimized. High power batteries are typically 30–50% more expensive and therefore not used in BEVs. The industrial average for battery pack size in a BEV is around 25 kWh, while sizes up to 85 kWh have been used by Tesla. [42] These prices apply to electric car batteries, which are produced in bulk and a direct comparison to batteries used in heavy machinery - such as LTO batteries - cannot be made. However, the decline in prices continues and the spillover of technical knowledge to battery-operated machinery could make heavy electrical machinery even more attractive than before.

The average energy content of 25 kWh in electric cars might not be enough for industrial machinery, that require several hundred kilowatts to operate, while electric cars only use an average of 0.20 kWh/km. [43] It is also worth noting, that the charging time is inversely related to the charging power and that the charging current has to be reduced when the battery nears 80% of its full capacity. After 80% the battery will charge at a considerably slower pace. [44].

In harbors, there is usually medium voltage available. Using higher voltage, higher charging powers could be achieved minimizing the required charging time. [8] However, the limitations of high power charging originate mainly from batteries.

If high power charging is not feasible during normal operation, battery swapping stations can be build instead. At these stations, the battery of an electrical drive is changed to a fully charged one replacing the need for charging breaks. The downside to this solution is that the battery warehouse would be very large due to the large size of the batteries. This method has already been used with AGVs and lead-acid batteries. [5] Another downside is that in Li-ion batteries, communication wires to BMS and liquid cooling lines have to be disconnected/connected during the swapping process, - in addition to the electrical connection - which makes the process more complicated than the swapping process of lead-acid batteries.

There are limitations in the charging process of batteries. As an example, Li-Ion LTO battery of 10 kWh - which is one of best batteries in terms of charging power acceptance - can be charged only up to an estimated power of 60 kW, meaning that a 500 kW charger can only charge batteries of over 83.3 kWh using full power. The reasons are largely due to high currents, which should be limited so that the C-rate stays around 6 C with current battery technology. This can also be expressed as power-to-energy ratio of 6, which is also used as a baseline in this thesis. C-rate means the charge and discharge rate of a battery. This means that a 4.2 Ah battery with C-rate of 10 can charge using 42 A current. [37, 44] Other sources cite the C-rate of LFP and LTO batteries to be 1 C and 4 C, respectively [40]. Even LTO batteries capable of 12 C are not impossible to find [37].

3.3 Charging system categories and standards

The development of charging technologies is led onward by electric cars, which is why this chapter mostly relies on information from those sources. The technologies could be implemented in industrial machinery as well, but the challenge is the large requirement for power, energy, and fast charging times. [37] The charging power is limited by battery technology, which was already covered in chapter 3.2.

The charging categories - plug-in, pantograph, and induction - discussed in this chapter can be further categorized into on-board and off-board systems, which apply mainly for battery-operated vehicles. In on-board systems, the charging power electronics are located in the vehicle. This charger is supplied with uncontrolled AC or DC current, that is then converted into controlled current to charge the battery. [37]

Correspondingly, in off-board systems, the power electronics are in a separate location outside of the vehicle. This reduces the weight of the vehicle and the charger can be used by multiple vehicles, which reduces costs. Controlled current is supplied to the vehicle battery and the charger communicates with the BMS. This communication requires the use of a special type of connector, which has to have poles for power transfer and communication. The connector can be a plug-in cable, such as Chademo or Combo-connector, or a special type of pantograph. [37]

Certain initial routines are carried out before the charging starts, such as ensuring that the connector is properly attached and there are no ground faults etc. Additionally, the previous SoC is a relevant information, because the charging should not start with 100% power if the battery is already full or almost full. Different communication protocols and standards exist depending on charger type. [37, 38]

Connecting the charger to the vehicle can be either manual or automatic depending on the technology. Automatic technologies ease the adaptation process of introducing new technology, while minimizing the possibility for human errors. Because of the future trends of harbor operations, the charging process used should be automatic instead of manual. Manual charging could be used during maintenance tasks, when there are usually other a human activities involved as well. [5]

3.3.1 Standards

For BEVs, there are numerous standards concerning charging and different types of plugs. The standards are presented in table 4. [43] Slow standardization has been one reason why charging technology of BEVs has developed so slowly [44].

Several standards have been issued for different charging methods. The international standard IEC 61851-1 defines the general requirements and properties for electrical vehicle charging, while EN 61851-1:2011 is the confirmed European standard for similar function. Two standards - IEC 61851-22 and IEC 61851-23 - add

Table 4: International standards of BEVs related to connectors, communication, safety, and charging topology. [43, 45]

International standards for the charging interface			
Connector	**Communication**	**Safety**	**Charging topology**
IEC 62196-1	ISO/IEC 15118	IEC 60529	IEC 61851-1
IEC 62196-2	SAE J2847	IEC 60364-7-722	IEC 61851-21
IEC 62196-3	IEC 61851-24	ISO 6469-3	IEC 61851-22
SAE J1772	SAE J2931	SAE J1766	SAE J1766
	IEC 61850	ISO J17409	ISO 17409

special requirements to the previous standards, the first covering the topic of AC charging and the second covering DC charging. [43]

Currently, there are four different recognizable situations, in which the previous standards apply to BEV charging. The charging method 1 covers charging of small electric vehicles, such as electric scooters, with single-phase 16 A AC. The second covers normal electric cars that use a single-phase household socket for charging. Continuous current has to be limited under the normal 16 A, which means that the available charging power is around 2 kW. The third charging method uses single or 3-phase charging, while the available maximum power can be up to 43 kW. The fourth method uses DC for fast charging the BEV, while the charging power can range from tens to hundreds of kilowatts. In this method, the charger is located outside the vehicle, and requires communication technology that controls the charging current. [43]

The high power charging is used especially in electric city bus charging, but currently there are no specific standards for it. Problems arise, if the electrical machinery and the charger do not have suitable connectors, which could be the case, if the manufacturers were different. [41] In harbor machinery, this problem can be avoided, if the container handling equipment manufacturer designs both the machinery and the charging equipment. This means that no standards are needed for the connectors. However, standards for safety are still necessary. [5]

3.3.2 Plug-in cable

Charging systems of electrical vehicles and cars can be categorized in three groups according to the speed of charging. These categories are slow, mid-range and ultrafast charging. The last one is also known as DC quick charging and DC fast charging. [44, 43]

The slow charging utilizes single-phase 120–240 V, which corresponds to a common household socket [44]. The maximum available power is 2.3 or 3.6 kW, depending on voltage. Maximum power for the mid-range charging is typically 11–22 kW and the charger typically uses a 3-phase system. The highest power available is achieved using an ultrafast charger, which can produce powers over 50 kW. [43]

As previously covered in chapter 3.2, charging a battery with high power decreases battery lifetime among other factors [44]. Slow charging is usually most suitable for depot charging [40].

The plug-in cable is common in electric cars and city buses. The plug-in cable is manually connected, which would require additional effort from the machine operator. It is best suitable for depot charging due to low charging powers. The low charging power together with manual connecting makes usability during operation difficult if not entirely impossible. [40]

The cost of plug-in cable charging infrastructure is low. Although, due to the small charging power the necessary battery energy content rises increasing the cost of a battery. [40]

The plug's structure and testing requirements are defined in standards IEC 62196-2, the European corresponding being EN 62196-2:2012. The standard defines three types of plugs: Yazaki, Mennekes and SCAME. A plug for DC charging is defined in standard IEC 62196-3. [43]

The Yazaki plug is also known as Type 1 or J1772, and it is used in North America. The Mennekes plug, also known as Type 2, was chosen to be the common European charging connector for BEVs. It is suitable for slow and fast charging using 1 or 3 phases. It enables a charging power of 43 kW. The European Commission's directive requires, that the fast chargers are also equipped with Combo 2 connector, which has a Mennekes connector in addition to the DC connector. SCAME is the Type 3 plug that is capable of charging 16–32 A with 250 V in single-phase mode and 32 A with 400 V in 3-phase mode.

CHAdeMO is a connector used in Japanese cars [43]. The current capacity of CHAdeMO is around 125 A, while the same figure for Combo 2 is around 200 A. These current limitations can oppose considerable restrictions for the charging. [37]

Using DC current, charging powers of 100 and 200 kW can be achieved. The charger in DC charging is always off-board. [43] This solution is not regarded as very feasible for harbor operations due to the low charging power and need for manual connecting. It would be most suitable for depot/maintenance charging, in which low charging power is enough. [5] The low charging power would also spare the battery from wear and increase its lifetime.

3.3.3 Pantograph

The pantograph can be used either dynamically with a pantograph-catenary (PAC) system presented in chapter 3.4.1 or with fixed charging system shown in figure 16. Both systems are automatic, but in the fixed charging system the pantograph can be located on the machinery or the charging device. [40] This chapter discusses mainly the fixed pantograph system - later addressed only as pantograph - because the PAC system is not entirely a battery-utilizing system.

The maximum available charging power of the pantograph is around 400–500 kW [40, 47, 48]. A pantograph can charge the electrical machinery without human interaction. This enables charging between work cycles during operation, which is also known as opportunity charging. [40]

Figure 16: Offboard charging with a pantograph [46].

The pantograph system is quite new technology in public transportation, which means that the production is still in its testing phase. Due to novelty of the pantographs, their standardization is still lacking. [40] This might create design difficulties for the container handling equipment manufacturer.

The pantograph system does not require very high precision. It allows lateral transition of about 0.5 meters and several meters lengthwise. The positioning can be improved using cameras or other equipment if needed. [40]

The cost of a pantograph is greater than that of the plug-in charging system, but the battery size can be smaller due to more frequent charging. The frequent charging also increases the battery lifetime because of lower DoD. [40] An estimated cost for an electric bus pantograph charger is about 250,000 € [49].

This system is regarded as most feasible due to its automatic nature, but some difficulties would have to be overcome. [5] One of the difficulties of quayside-to-yard machinery is that containers are loaded on top of the machinery making pantograph placement impossible. With shuttle carriers, the problem is the tall height, which would make the pantograph poll very tall as well, which increases costs. The pantographs for electric city buses are over 3 meters tall, which might be too low for some harbor machinery [40]. Implemented on the backreach area of the STS crane, it might increase the risk of collision. Proper design should be carried about and different integrated solutions with the STS crane could be sought.

3.3.4 Induction

An inductive charging system is automatic and contactless. It is presented in figure 17. The main components are high-frequency converter, primary coil, secondary coil, rectifier, and communication. The high-frequency converter converts supply voltage into high frequency AC for the primary coil. When the vehicle's secondary coil is positioned over the primary coil, the secondary coil lowers near the primary coil and inductive power transfer is initiated. The high-frequency AC voltage from the secondary coil is rectified for the battery. The vehicle-to-infrastructure communication is wireless and the charging process can be controlled by the distance of the coils or the high-frequency converter. [37, 40]

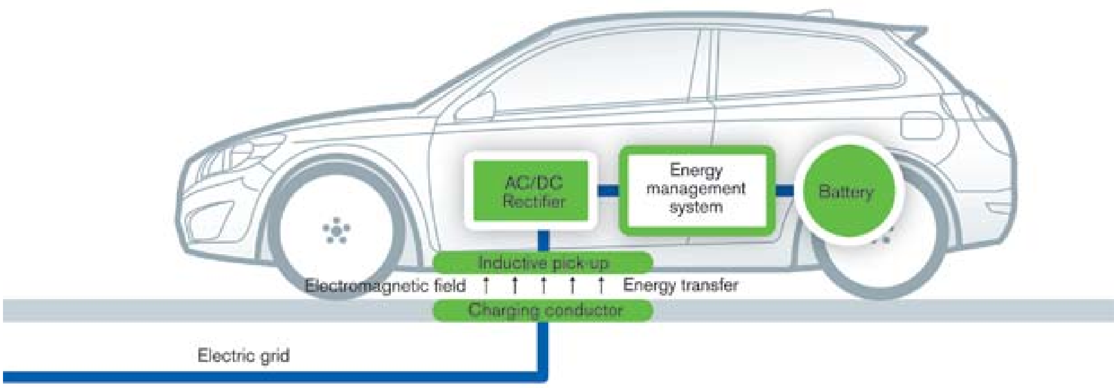

Figure 17: Induction charging of a vehicle [50].

The available charging power is around 100–200 kW. Dimensions for a typical primary coil are: 3–5 m in length and 1–2 meters in width. The installment depth is usually about 1 meter. The induction charger is relatively expensive as a charging system due to the coils. [40]

In inductive charging systems, there are similar risks involved as in pantograph systems due to a lack of standards, but the usability is also uncertain. Positioning of induction charging is very precise requiring automatic detection technology, while the charging can fail due to a number of factors, for example ice, snow, trash, and sand. [40]

The feasibility of this technology is highest in AGVs, masted container handlers, reach stackers, forklifts, and terminal tractors due to their low height, and because the container is not located at the bottom. Conversely, for example shuttle carriers and straddle carriers attach on top of the container, which makes locating the secondary coil at the bottom of the machinery nearly impossible without the distance of the coils being too far. Other placement options for the secondary coil, such as on top or on the side of the machinery, should be investigated. [5]

3.4 Grid supply technologies

This chapter discusses supply technologies, that supply the vehicle straight from the grid. The technologies are overhead line and rail, and trailing power cable. Supplying electricity straight from the grid means, that the vehicle does not need a battery in order to function properly. The supplied electricity is uncontrolled AC or DC, which is converted for the electric motor. Due to the lack of a battery, there is no need for communication signals, that would interact with the BMS. This simplifies the structure of the supply equipment. [37]

The grid effects of the charging must be examined before the charging infrastructure can be implemented. The more power is drained from the existing grid network, the more effects it causes. In a worst case scenario the charging could overload the grid. The main transformer and cables could require resizing if the necessary power taken from the grid is too much for the existing system. [51] The basic requirement is that they follow the basic grid codes of the operating country [37].

3.4.1 Overhead power line and rail

The use of an overhead power line in supplying electricity to a machine is similar to a tram's power supply. The supply method utilizes one or two roof-mounted trolley poles, which are used to conduct direct current (DC) to the machinery. The amount of trolley poles depends on whether the machinery operates on rubber tires or rails. In the case of rubber tires, there are two trolley poles, one of which is connected to the positive wire and the other is connected to the negative wire. This method is presented in figure 18. If the machinery operates on rails, only one trolley pole is necessary as the rail works as a return path for the current. [26]

For trolley buses, the existing power supply ranges from 600 V to 1000 V [26]. The Finnish tram system utilizes a 600 V supply, while the subway system uses 750 V [53]. Increasing the supply voltage would decrease conducting losses as the power losses are dependent on the square of the current. Additionally, the necessary diameter of the wires could be reduced, which would create costs savings when building the infrastructure. [26] Another reason to increase the supply voltage is that the efficiency of regenerative breaking increases [53]. The efficiency of trolley buses is found to be around 81%, while the efficiency decreases to 69%, if losses in transformers and overhead power lines are included [26].

The route of the electrical machinery would be fixed in the case of the overhead line, because of the stationary nature of the overhead wires. If some additional degrees of freedom are required, the machinery could use auxiliary power units (APU), when the overhead wires are not available. The APU could be an internal combustion engine (ICE) or an on-board energy storage system (ESS) such as a

Figure 18: Overhead power line [52].

battery or a super capacitor. The APU would enable the machinery to pass obstacles that block their normal operation, or the machinery could locate to another fixed route. This would make the system less vulnerable to disturbances. The APU could also be used at the depot, where there is no overhead line infrastructure [26]. The use of an APU could be necessary at the back reach area, since the container is lowered from above for AGVs and on the route of shuttle carriers making overhead cables impossible to situate without interfering with the container lowering. For a shuttle carrier, the height of the overhead wire would have to be over 10 meters, which would be very difficult - if not entirely impossible - to implement and maintain [19].

In trolley bus operation, it is necessary that substations are built every three line kilometers for an even supply. The required infrastructure increases the initial investment costs greatly compared to those of the diesel alternative. [26] In harbor operations the investments in infrastructure might not be so great as distances in harbor environments are not that long [5].

The cables of the overhead power line might be hazardous in harbor conditions as other machinery might be necessary in the same area. It is especially true since space is limited, which would require additional precautions. The cable infrastructure is generally considered as not very aesthetic, which further makes it an unpopular choice. Currently, building the necessary infrastructure in harbor is not considered a realistic option, because of its challenges and high initial investment cost. [5]

3.4.2 Trailing power cable

Trailing power cable technology uses a power cable that trails behind the electrical machine supplying it constantly. It is connected to a suitable electrical infrastructure, and can be assisted with a reel, that feeds the cable. In certain environments it is regarded as the most suitable way to power machinery. For example in mines eLHDs represent such machinery. Due to the characteristics of the attached cable, some limitations arise such as reduced mobility and versatility, and cable and relocation issues. There are additional issues with cable reels and their costs. Despite the multitude of these problems, some of their issues can be reduced by proper design of the operating environment. [1]

A trailing cable ensures a constant supply for the machinery, but it is subjected to wear and tear as it is pulled and dragged on the ground. Regular maintenance and condition checks should be made to ensure that that cable has remained intact. In some cases, these cable problems cause unnecessary decrease in productivity, which makes the cables suitable for only certain operating environment layouts, work cycles, and work habits. For example, if the machinery would always be facing the same direction, it would reduce cable wear. In a study conducted in Australia, it was found that 15% of eLHD maintenance occurred because of the trailing cable problems and other electrical faults, while the same figure for a diesel LHD was 6%. Despite all the benefits of electrical machinery, it is argued that the tethered electrical machinery cannot beat the versatility of diesel engines. [1]

4 Total cost of ownership of electrical machinery

Due to the often lower operating costs, but higher initial investment costs, the TCOs of battery electrical machinery and charging infrastructure with different charging concepts are relevant to estimate before making product development strategies and investment decisions. The concepts studied in this thesis are opportunity and depot charging. The calculations require estimates on operation profile, power demand, and energy consumption of the vehicles. Dimensioning of batteries and charging systems is based on these factors. The initial investment costs are assumed to only consist of the battery and the charging equipment. Other costs such as motors and machine structures are omitted, because they are difficult to estimate.

In larger perspective, the dock container handling operation is a multi-parameter optimization challenge, in which operation speed and the number of STS cranes have an effect on the optimal amount of other machinery. Numerous studies have been conducted to optimize the amount of vehicles, costs and handling time in container handling operations. [54, 55, 56]

In the generic operations models, the effects of available charging time and power on different machinery are studied to form a comprehension about different operating scenarios, limitations, and dependencies involved. For example, knowledge of the minimum amount of battery energy content is required. Generally, the less charging time there is available, the higher the charging power must be, if the charging duration is kept constant. Also, the more power is consumed during a work cycle, the higher is the necessary battery energy content. Larger batteries also mean higher battery costs, but they can also increase battery lifetime, because a lower DoD is achieved. The two models studied in this chapter comprise of opportunity charging, in which natural pauses of the operations are utilized for charging, and of depot charging, in which the machinery charges only at the depot once the battery is empty. The results are general without focusing on any specific type of container handling machinery. However, the operations mainly focus on the quayside-to-yard machinery, because the quayside and the yard can already operate using only electrical machinery, and suggestions about machinery, that are suitable for electrification, are made.

After the generic models are developed, the costs of different solutions are discussed on per hour basis in chapter 4.2, and compared to the hourly cost of using diesel machinery. The hourly cost includes the initial investment and operating costs. Afterwards, sensitivity analyses are performed on variables to identify key variables that affect the TCOs the most.

Limitations of the models that affect the TCO estimates are discussed in chapter 4.3. They act as a basis for further study together with the results of the sensitivity analyses. Further study should focus on removing uncertainties from the models.

4.1 Generic models of harbor operations

Estimates of average machinery power, cycle time, and available charging time can be used to calculate a required charging power and battery energy content to complete one full work cycle. Existing diesel-operated machinery can be utilized to measure more accurate estimates when designing the battery-operated machinery for a harbor.

To evaluate the feasibility of different electrical machinery and charging concepts, some assumptions are made:

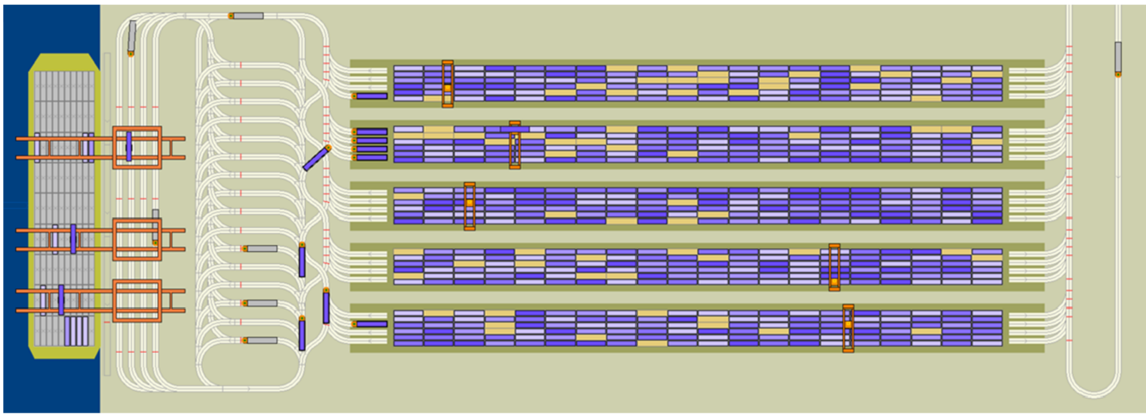

Figure 19: An illustration of the operating environment [57].

- There is no congestion, only one quayside-to-yard machine is operated at a time.
- It takes 1–5 minutes for the machinery to deliver the container to its destination, afterwhich the machine returns to the quayside and waits until the next cycle begins. This duration, during which the machinery is moving, is later expressed as "operating duration".
- Average power of a diesel operated machinery is 16.7–25% of the peak diesel power rating. Thus, the average power ranges between 20 and 80 kW. The range is divided into 20, 40, 60, and 80 kW scenarios.
- The power consumption is steady during operation and 0 kW during charging period.
- Maximum available charging power is 500 kW.
- Maximum power acceptance of the battery is 60 kW per 10 kWh.
- Starting and ending the charging process is immediate.
- Charging is 100% efficient.
- The battery's energy density is 0.1 kWh/kg.
- The battery's power density is 0.4 kW/kg, which is lower than previously presented in chapter 3 due to battery packaging.

Next, the minimum design criteria are calculated for the opportunity and depot charging concepts using different average machinery power values, and compared between different scenarios. The feasibility of the different scenarios is also evaluated critically.

4.1.1 Opportunity charging

The opportunity charging concept utilizes waiting periods between each work cycle to charge the battery. Utilizing these waiting periods enables the vehicle to use a smaller battery, because the energy consumed per cycle is always replenished, and the consumption period is short. However, due to the nature of the work cycles in harbor operations, the charging window is also usually short, which means that the charging power requirement is high. In reality, additional time is required to start and stop the charging process.

The main design questions in the opportunity charging concept are simple, and they usually include some trade-offs. How much time is there available for charging during each work cycle? How much charging power is required to replenish the consumed energy in the available time window? How long should the machinery be able to operate? How much battery energy content does the machinery require in order to complete the desired amount of work cycles? How many vehicles are used? The design might be different for different harbor layouts, because work cycles vary.

An ideal opportunity charging system enables the operation to run continuously without additional artificial charging breaks, that would disrupt productive activity. The continuous operation is especially useful in large harbors, where the operation runs around the clock. For continuous operation, the charged energy during a break should equal the energy consumed during a work cycle.

The basic design equations are simple. The amount of energy E_1 used by a machine is the product of average power consumption P_1 and operating duration t_1:

$$E_1 = P_1 t_1 \tag{1}$$

In opportunity charging, the amount of energy E_2 charged per cycle should be at least as much as the energy consumed per cycle:

$$P_1 t_1 \leq P_2 t_2, \qquad \text{where } P_2 \gg P_1 \text{ and } t_2 \ll t_1 \tag{2}$$

Calculating E_2 is similar to calculating E_1, but generally the charging power is much higher than the average power consumption, and charging duration much lower than operating duration.

Figure 20 presents a contour graph and a bar graph of different charging durations for an electrical machine that uses 20 kW of average power. The charging duration is affected linearly by operating duration and exponentially by charging power. Additionally, having a more powerful charger reduces variation in charging durations, which can be seen from the bar graph as a decreasing steepness of the bars. Determining a suitable charger power can be done, if the worst case average

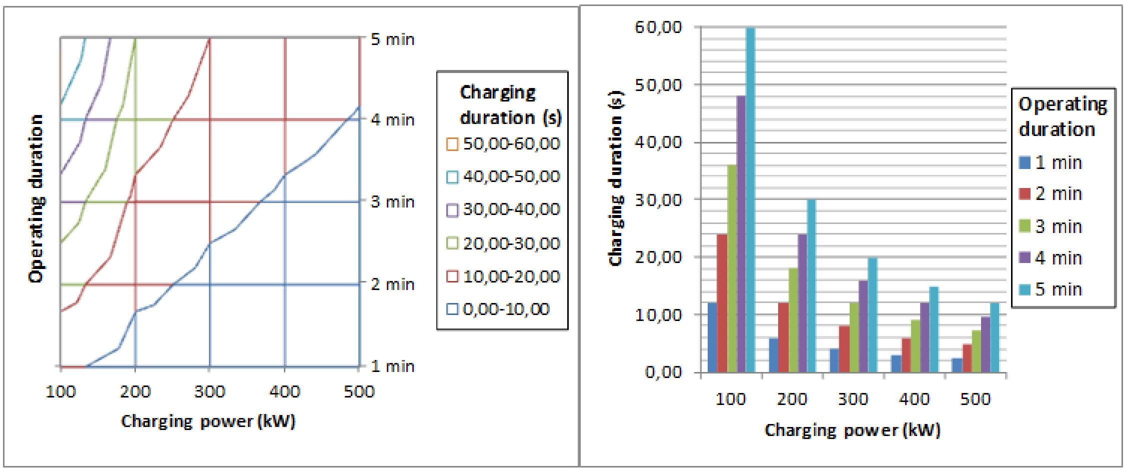

Figure 20: A contour graph (left) and a bar graph (right) of 20 kW machinery representing required charging duration as a function of charging power and operating duration.

power consumption and operating duration per cycle are known. Charging duration is usually determined by other machinery. Selecting a higher charging power allows more estimate errors. As an example, if the machinery uses 20 kW average power, and the operating duration per work cycle is 3 minutes, and the available charging duration is 20 seconds, then about 200 kW of charging power is enough. A charger of 250 kW could be chosen to provide some safety margin.

Doubling the machinery power to 40 kW also doubles the charging durations for every comparable situation, which can be seen by comparing the previous figure and figure 21. Using 100 kW of charging power in 5-minute operations, it now takes 120 seconds - instead of 60 seconds - to achieve a full charge. To accomplish the former charging duration of 60 seconds, the charging power has to be doubled to 200 kW.

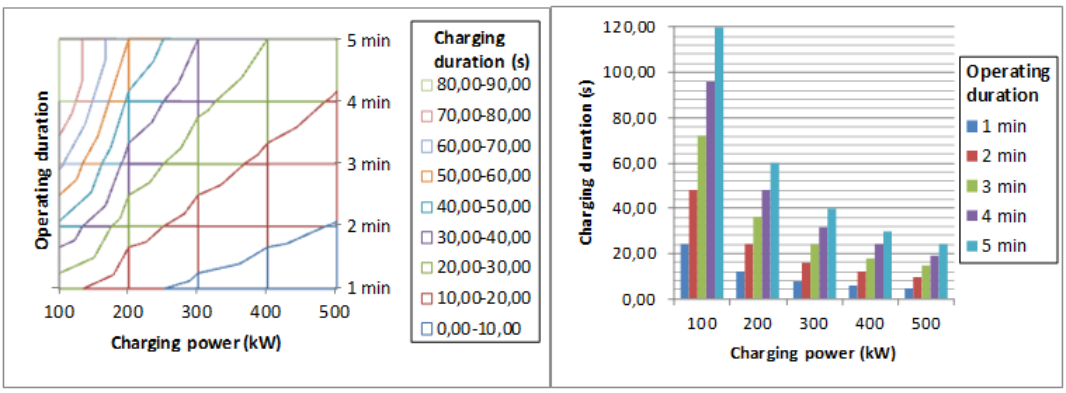

Figure 21: A contour graph (left) and a bar graph (right) of 40 kW machinery representing required charging duration as a function of charging power and operating duration.

From the previous figure, it can also be noted that some scenarios are not feasible anymore. If the operating duration is longer than 2 minutes, even the 500 kW charger cannot achieve charging duration of under 10 seconds to replenish the same amount of energy that was used.

The higher the machinery power rises, the more the charging duration varies, which can be seen by comparing the bar graphs of figures 20 and 22. A 60 kW average power consumption is roughly that of a shuttle carrier or a reach stacker. Because of the high energy consumption, some charging scenarios are no longer feasible. For example, the 100 kW charger is not enough to charge the machinery under one minute, if the operating duration is over 1 minute. Assuming a 20 second connecting duration and 1 minute break, only the 500 kW charger is able to provide enough energy for every operating duration up to 5 minutes.

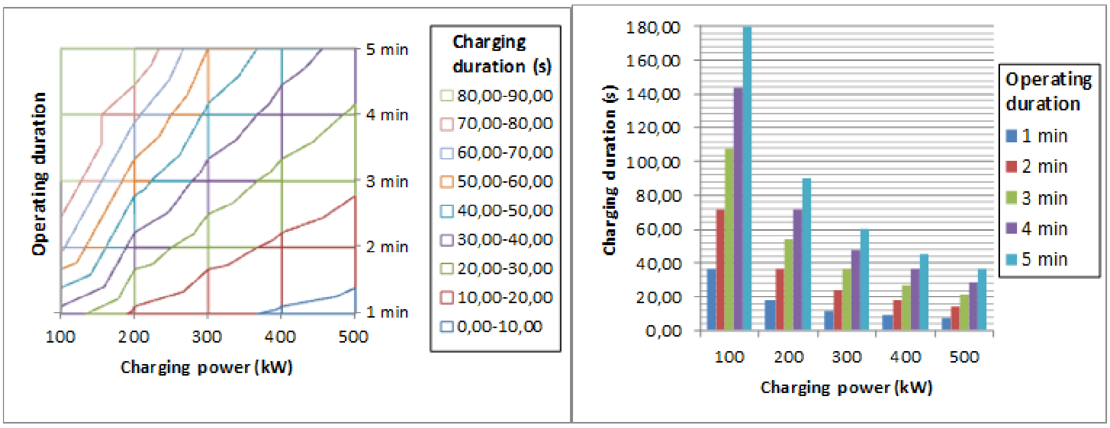

Figure 22: A contour graph (left) and a bar graph (right) of 60 kW machinery representing required charging duration as a function of charging power and operating duration.

For the 60 kW machinery, a minimum of 300 kW of charging power is enough so that the machinery can operate in a full range and charge under a minute. A 80 kW machinery in a similar situation requires a minimum of 400 kW of charger power. This can be seen from figure 23. Using a 80 kW machinery, it is no longer possible to charge the machinery in under 10 seconds. For machinery, that has as high average power consumption as 80 kW, it can be recommended that the highest available charging power of 500 kW is used, which provides some safety margin in operations.

All the cases presented earlier only consist of one machine operating at a time, and charging after each cycle. The amount of machinery can be increased as long as the charging power is adjusted accordingly. It should be noted that the figures do not apply in the case of multiple vehicles. As an example, using five 40 kW machines - which roughly equates to five AGVs - and a operating duration of 3 minutes gives a charging duration of:

$$\frac{3 \cdot 60s}{5-1} = 45s \text{ per vehicle} \tag{3}$$

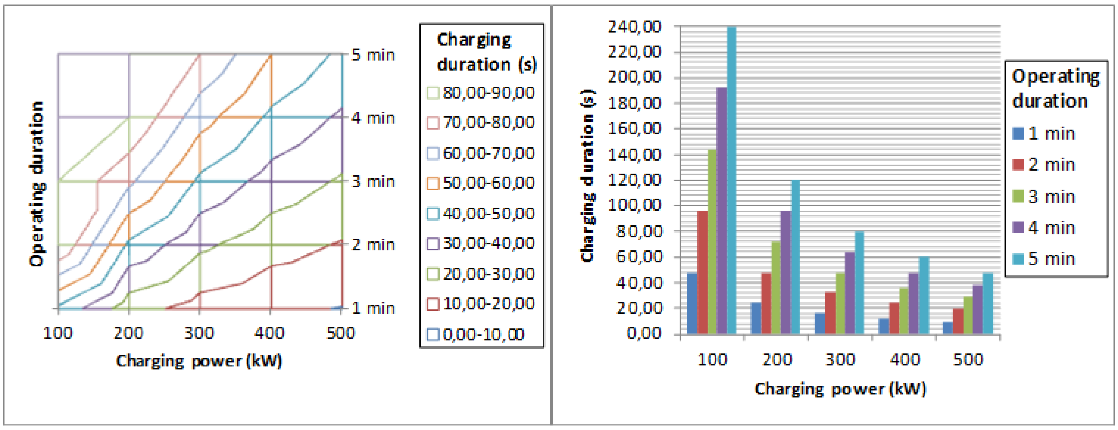

Figure 23: A contour graph (left) and a bar graph (right) of 80 kW machinery representing required charging duration as a function of charging power and operating duration.

before the next vehicle arrives. The duration is 45 seconds instead of 36 seconds, because one vehicle is always charging and the rest are operating. A vehicle lags 45 seconds behind the next vehicle.

The second major design criteria is the battery energy content. The minimum amount of energy required to complete one full work cycle is defined by the machine power and operating duration. In figure 24, the influence of these two factors to the battery energy content is studied. A 60 kW machinery that operates for 3 minutes needs at least 3 kWh of energy. The energy requirement rises linearly according to machinery power. Additionally, the minimum energy requirement varies more in higher power machinery, if the operating duration is not constant.

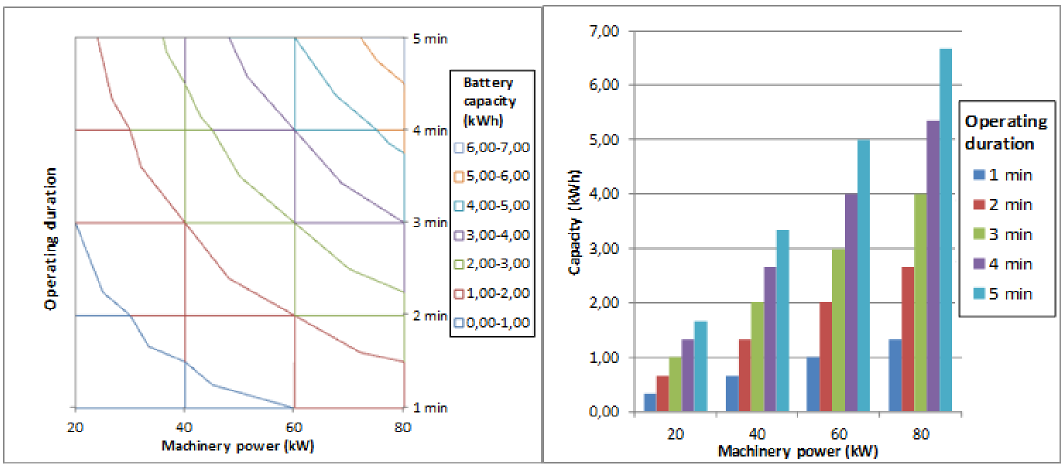

Figure 24: A contour graph (left) and a bar graph (right) of battery energy content required to complete one full work cycle as a function of average machinery power and operating duration.

These capacities only represent the requirement set by one work cycle. Using an 80 kWh battery, a 80 kW machinery can complete 20 full 3-minute work cycles, which provides the operations some margin of safety. This 1-hour full operating time could roughly correspond to the amount of time one ship is docked, afterwhich there is some time left for charging before another ship has been attached to the dock. An additional benefit is that the machinery operator does not have to charge the machinery during every cycle, which might decrease frustration and opposition against new technology. More operating time is also an advantage when the machinery is relocated to another berth or to an overnight depot, which might be located far away from the docks.

The battery dimensioning should be carried out with the battery lifetime in mind. In the previous scenario, charging after completing 10 full work cycles would mean a DoD of about 50 %, which is still quite high. Remembering figure 15 from chapter 3, it can be said that smaller DoD rates increase the battery lifetime exponentially. The design should also note that the battery is still usable after a portion of the capacity has been degraded, but the dimensioning should also be done in such a matter that the degradation does not interfere with the normal operation.

Using an energy density of 0.1 kWh/kg, the 80 kWh battery would weigh about 800 kilos, which is manageable since the harbor machinery themselves are quite heavy. Weights of up to several tonnes should not be an issue, but this is more up to the machinery manufacturer. Another factor is the battery volume, which opposes some limitations, because harbors are narrow and large volume would leave less space for other equipment.

To summarize, the opportunity charging concept is suitable in harbors, in which the operation needs to be continuous. The feasibility of electrical technology in those operations depend largely on the operating environment and the key factors of average machinery power, operating duration, available charging duration, and fleet size. These factors are different in each harbor so the design would have to be customed to achieve optimal design.

4.1.2 Depot charging

In the depot charging concept, the machinery is operated until the battery has been drained completely, and needs to be recharged at the overnight depot. The concept is similar to that of a diesel-operated machine. Usually the charging can be done using smaller charging power, which might increase battery lifetime depending on battery type. The depot charging is a suitable method in operations, in which there are no pauses between cycles or for machinery that does not require waiting such as the shuttle carrier. Key differences of depot charging compared to opportunity charging are higher battery energy content and lower charger power.

Operating the machinery for a full day or a part of the day requires larger battery sizes than in the opportunity charging method. Figure 25 shows the effect of machinery power and length of operating duration in hours to the minimum requirement of energy. All these scenarios have 100% DoD, which is not very feasible. Increasing the capacities by 25% lowers the DoD to 80%. For the battery type used in depot charging concept, 1 kWh roughly translates to 10 kilos of weight, which makes some of these operating scenarios not feasible. The 8-hour operation of smaller harbors should be feasible for all machinery powers presented here, but some of the capacities related to over 16-hour operation might be too large.

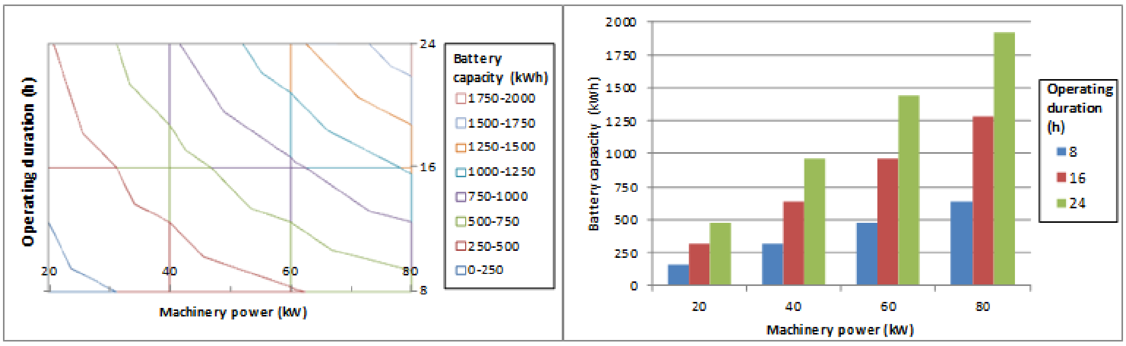

Figure 25: A contour graph (left) and a bar graph (right) of battery energy content as a function of machinery power and work shift length.

In some cases, the 24-hour operation using the depot charging is not feasible, if there is no time left to charge the battery before the next shift starts. This would require that additional machinery is used to compensate the lack of available machinery leading to a low capacity utilization rate of the machinery. The charger, however, could be in full use all the time. In order to increase the machinery utilization, a battery exchange concept could be used together with the depot charging concept.

The lowest necessary charging power can be calculated, if the battery energy content and the amount of charging time are known. For a 60 kW machinery with a 500 kWh battery, that operates 8 hours per day, the idle time is 16 hours, which gives a minimum charger power of:

$$P = \frac{E}{t} = \frac{500\text{ kWh}}{16\text{ h}} = 31.25\text{ kW} \tag{4}$$

Having four of these machines would decrease the available charging duration to 4 hours and increase the charger power to 125 kW, if there were only one charger in use.

The feasibility of depot charging is currently poor due to the high energy content requirement, which causes batteries to be large, heavy, and expensive. Also the charging duration might be too long in some cases.

4.2 Cost of different solutions

The difficulty of assessing the costs of electrical drives and infrastructure lies in complexity and lack of public data, which means that estimates might vary greatly. Data is usually confidential due to the competitive nature of equipment manufacturing.

However, simple TCO models can be built and the cost structure can be studied by using sensitivity analysis to reveal the effect of underlying variables on the outcome. Sensitivity analyses in this chapter are presented so that only one variable is changed at a time. The models developed in this chapter are cost per hour based for machines that use about 40 kW average power. The TCO models in this thesis do not include the cost of machinery structure, motor, nor personnel, which can be added later. The models only iclude the cost of energy, battery, and infrastructure.

The cost of owning and using electrical machinery comprises of several factors. In this thesis, only the basic costs are estimated, while the rest are listed in chapter 4.4 as limitations of the cost model. In this chapter the costs of opportunity and depot charging concepts are estimated and compared to the cost of using diesel machinery. Using these estimates, a payback time and profitability can be presented.

A comparable diesel machinery is the Konecranes reach stacker (diesel engine on make Volvo and model TAD-1340-VE), which has a fuel consumption of 12–16l/h and a rated power of 256 kW [58]. This is assumed to be closely comparable to an electrical drive of 40 kW average power consumption, when the diesel engine efficiency is around 29%. The cost of a diesel liter is assumed to be 1.00 €/l, which gives a total cost of 14.00 € per hour. Sensitivity analysis for the price and consumption of diesel is presented in figure 26 In this case, one liter change in average consumption has less effect on the total cost per hour than a 0.20 € change in diesel price. It is also noteworthy that diesel price differs widely by country.

Diesel price (€/l)	0,60 €	0,80 €	1,00 €	1,20 €	1,40 €
Total cost per hour	8,40 €	11,20 €	14,00 €	16,80 €	19,60 €
Consumption (l/h)	10	12	14	16	18
Total cost per hour	10,00 €	12,00 €	14,00 €	16,00 €	18,00 €

Figure 26: Sensitivity analysis of the cost of using diesel machinery.

4.2.1 Cost of opportunity charging concept

To assess the costs per hour of using electrical machinery utilizing the opportunity charging concept, a base case was developed. Some of the key variables and default values, that affect this study, are listed in table 5:

Assuming a machinery power of 40 kW and a battery size of 40 kWh, we can derive the total operating duration of:

$$E = \frac{40 \text{ kWh}}{40 \text{ kW}} = 60 \text{ minutes}, \tag{5}$$

which means that the amount of full 4-minute operating cycles is:

$$\frac{60 \text{ min}}{4 \text{ min}} = 15 \text{ cycles}. \tag{6}$$

Using a fleet size of 5 vehicles, the average charging duration per vehicle is 60 seconds. The battery allows a maximum charging power of 240 kW, which charges the energy

Table 5: Base case values for the opportunity charging concept

Variable	**Value**
Yearly usage:	5,860 h
Machinery power:	40 kW
Battery energy content:	40 kWh
Operating duration per cycle:	4 min
Battery cost:	1,000 €/kWh (LTO)
Battery lifetime:	10 years
Battery power acceptance, P/E:	6
Charger cost:	250,000 € [49]
Charger holding period:	10 years
Fleet size:	5 vehicles
Electricity cost:	0.10 €/kWh
System energy efficiency:	75%
Interest rate:	10%
Residual value:	Zero

used during 4 minutes in 40 seconds. The charging duration can be decreased by increasing battery size or improving battery power acceptance.

The charger cost of 250,000 € is divided by the yearly usage hours, charger lifetime, and fleet size. This results in a charger cost of:

$$\begin{aligned}\frac{\text{Charger cost}}{\text{Yearly usage} \cdot \text{Lifetime} \cdot \text{Fleet size}} &= \frac{250,000 \text{ euros}}{5840 \text{ hours} \cdot 10 \text{ years} \cdot 5 \text{ vehicles}} \\ &= 0.86 \text{ euros per hour.}\end{aligned} \tag{7}$$

The hourly cost of a battery is calculated similarly to charger cost, but the battery cost is formed of the required energy content and the unit cost of kWh, and the cost is not divided by fleet size since they each need their own battery. Using a 40 kWh battery would cost:

$$\begin{aligned}\frac{\text{Battery cost}}{\text{Lifetime usage}} &= \frac{\text{Energy content} \cdot \text{Unit cost of kWh}}{\text{Yearly usage} \cdot \text{Lifetime}} \\ &= \frac{40 \text{ kWh} \cdot 1000 \text{ euros/kWh}}{5840 \text{ hours} \cdot 10 \text{ years}} = 0.68 \text{ euros per hour.}\end{aligned} \tag{8}$$

Some uncertainty is related especially to the lifetime of the battery as it depends on multiple variables. By proper operation, the battery could last around 10 years after which the battery can only hold a partial charge.

The cost of energy is created by electricity, which is the fuel of electrical machinery and therefore similar to diesel fuel in combustion engines. The cost of electricity comprises of several factors: electricity production, transmission, and taxes. In the TCO calculations, these factors are combined to form the price of electricity. It should be noted that in the hourly cost of energy, the full hour is not consumption, because a part of it is needed for charging. It is dependent on charging power, operating duration, and machinery power. The average operating duration per hour for the 40 kW machinery and 4-minute operating duration is:

$$\frac{4 \cdot 60 \text{ sec}}{40 \text{ seconds} + 4 \cdot 60 \text{ sec}} \cdot 60 \text{ min} = 86\% \cdot 60 \text{ min} = 51.43 \text{ minutes.} \tag{9}$$

Using equation 9 and the base assumptions the price per hour of energy for the 40 kW machinery is:

$$\begin{aligned} &\text{Price of electricity} \cdot \text{Avg. consumption per hour} \\ &= \frac{\text{Price of electricity} \cdot \text{Machinery power} \cdot \text{Avg. operating duration per hour}}{\text{Efficiency}} \\ &= \frac{0.1 \text{ euros/kWh} \cdot 40 \text{ kW} \cdot 51.43 \text{ min}}{75\%} = 4.57 \text{ euros per hour.} \end{aligned} \tag{10}$$

The TCO of the opportunity charging concept totals in 6.11 €/h, which is 7.89 € lower than the TCO of diesel machinery. The battery's proportion of the TCO is 11%, while the proportions of the charger and electricity are 14% and 75%, respectively. However, the sensitivity of the TCO has to be analyzed as well. The studied variables are: yearly usage, battery size, fleet size, unit cost of kWh, charger cost, charger and battery lifetimes, electricity price, system efficiency. The analysis is presented in figure 27. The yearly usage hours in the figure represent 8, 14, 16, 20, and 24 hours

Yearly usage (h)	2920	4380	5840	7300	8760
Total cost per hour	7,65 €	6,63 €	6,11 €	5,80 €	5,60 €
Battery size (kWh)	20	30	40	50	60
Total cost per hour	5,20 €	5,73 €	6,11 €	6,42 €	6,68 €
Fleet size	2	3	4	5	6
Total cost per hour	7,40 €	6,68 €	6,33 €	6,11 €	5,97 €
Unit cost of kWh (€)	400 €	600 €	800 €	1 000 €	1 200 €
Total cost per hour	5,70 €	5,84 €	5,98 €	6,11 €	6,25 €
Charger cost (€)	150 000 €	200 000 €	250 000 €	300 000 €	350 000 €
Total cost per hour	5,77 €	5,94 €	6,11 €	6,28 €	6,45 €
Charger lifetime (years)	6	8	10	12	14
Total cost per hour	6,68 €	6,33 €	6,11 €	5,97 €	5,87 €
Battery lifetime (years)	6	8	10	12	14
Total cost per hour	6,57 €	6,28 €	6,11 €	6,00 €	5,92 €
Electricity price (€/kWh)	0,08 €	0,09 €	0,10 €	0,11 €	0,12 €
Total cost per hour	5,20 €	5,66 €	6,11 €	6,57 €	7,03 €
System efficiency (%)	69 %	72 %	75 %	78 %	81 %
Total cost per hour	6,51 €	6,30 €	6,11 €	5,94 €	5,77 €

Figure 27: Sensitivity analysis of TCO of the 40 kW machinery using opportunity charging concept.

used during 365 days per year. Decreasing the usage hours has a large impact on the cost per hour since costs are divided by less hours. Changing battery size does not change the cost too much, because the battery is relatively small in opportunity charging concept. However, a decreasing fleet size has an increasing effect on cost since charger cost is divided by less vehicles. Due to the small size of the battery, the unit cost per kWh only has a slight influence as well. The impact of charger cost itself is not very great, because the cost is divided by five vehicles, but in conjuction with a decreased fleet size the influence would be drastic. Charger and battery lifetimes have quite equal but low effect on total cost. Electrical machinery should be favored in countries, where electricity is relatively cheap and diesel is relatively expensive, because the effect of 1 cent is almost 50 cents, which is a lot compared to effect of other variables. System efficiency does not have a large effect on the TCO even though high efficiency saves energy, which is almost 75% of the total cost. It should be noted that each of the total hourly costs in the sensitivity analysis are below the most pessimistic cost estimate (8.40 €/h) of using diesel machinery. The sensitivity analyses for 20, 60, and 80 kW machinery are presented in appendix A.1. Based on these findings, further study can be targeted at relevant areas.

The TCO calculations presented here do not account for electrical braking. The cost of energy is also a majority (75%) of the TCO. This makes studying electrical braking and other means to lower the cost of energy worthwhile.

Based on the results, it can be inferred that the most viable machinery for electrification is the AGV. The reason lies in the high fleet size (about 5 per STS crane), while only 3 carrier cranes are used per one STS crane. Both of these machines have quite predictable operating paths, but still AGV might operate more predictably because of its lower versatility compared to container carriers. The AGV is unable to stack containers, which makes it only suitable to carrier containers from the STS crane transfer are to the container yard transfer area. Additionally, the AGV cannot lift a container, which means that it has to wait until the container is lowered/lifted. This provides feasible operating breaks for opportunity charging. Due to the design of the AGV, any charging equipment would have to be attached from below or side to the vehicle. Designing the placement of the connectors and equipment should not be too difficult, and existing knowledge about the charging of electric cars and buses can be used for harbor machinery as well.

Profitability and cash flow for the baseline case are described in appendix B.1 as well as sensitivity analyses for the savings generated and NPV calculations using different initial investment values. The base case calculations assume that yearly savings are generated by the difference in cost of energy and initial investment costs are caused by the battery and charging infrastructure due to a lack of more data. The calculations show that the investment is profitable for the given values.

4.2.2 Cost of depot charging concept

Calculating the TCO for the depot charging concept is more simple than for the opportunity charging concept due to less complex operation. Key variables and default values, that affect the TCO of depot charging, are presented in table 6.

Using these base case variables, the cost of the depot charging concept per hour

Table 6: Key variables and default values for the depot charging concept

Variable	**Value**
Yearly usage:	5,860 h
Machinery power:	40 kW
Operating duration:	16 h
Battery energy content	640 kWh
Battery cost:	600 €/kWh (LFP)
Battery lifetime:	10 years
Charger cost:	30,000 € [43]
Charger holding period:	10 years
Fleet size:	1 vehicle
Electricity cost:	0.10 €/kWh
System energy efficiency:	75%
Interest rate:	10%
Residual value:	Zero

is 12.42 €, which is 1.58 € cheaper than the cost of using diesel machinery. However, the initial investment costs amount to 414,000 €, while the yearly savings are only around 50,613 €. Profitability and cash flow analysis are presented in appendix B.2.

In the base case, the cost per hour of the charger is only 0.51 € (4% of TCO), because of the low power requirement and cheap charger. Because of the nature of the depot charging concept, the size of the battery is over ten times larger than the battery used in the opportunity charging concept. The cost of the battery per hour per vehicle is 6.58 €, which is a significant portion (53%) of the total cost per hour. The battery cost per hour can not be decreased by adding more vehicles, because each of the vehicles needs an own battery. The second largest cost is electricity, which costs 5.33 € per hour (43%). The cost is greater than in the opportunity charging concept, because the full hour can operated and charging breaks are not necessary.

The sensitivity analysis of depot charging studies less variables than what were included in the sensitivity analysis opportunity charging. The variables are: yearly usage, unit cost of kWh, fleet size, charger cost, battery and charger lifetime, electricity price, system energy efficiency. It is assumed that the operating duration is directly derived from the yearly usage and battery size from daily operating duration, which is why their change is only studied through the yearly usage hours. The sensitivity analysis is presented in figure 28. The key factors can now be identified from the sensitivity analysis more clearly than previously. This time the key variables, that affect the cost of the battery can cause the TCO to be under or over the baseline TCO of the diesel machinery. Other variables such as yearly usage, fleet size, charger cost and lifetime, electricity price, system efficiency do not have a significant effect on the TCO. The effects are about 1.00 € per hour or under. The effect of fleet size is especially interesting since does not have any impact. This is due to the fact that each vehicle needs an own battery and a charger.

Yearly usage (h)	2920	4380	5840	7300	8760
Total cost per hour	12,94 €	12,59 €	12,42 €	12,32 €	12,25 €
Unit cost of kWh (€/kWh)	200	400	600	800	1000
Total cost per hour	8,04 €	10,23 €	12,42 €	14,61 €	16,81 €
Fleet size	1	2	3	4	5
Total cost per hour	12,42 €	12,42 €	12,42 €	12,42 €	12,42 €
Charger cost (€)	10 000 €	20 000 €	30 000 €	40 000 €	50 000 €
Total cost per hour	12,08 €	12,25 €	12,42 €	12,59 €	12,76 €
Charger lifetime (years)	6	8	10	12	14
Total cost per hour	12,76 €	12,55 €	12,42 €	12,34 €	12,28 €
Battery lifetime (years)	6	8	10	12	14
Total cost per hour	16,81 €	14,07 €	12,42 €	11,33 €	10,54 €
Electricity price (€/kWh)	0,08 €	0,09 €	0,10 €	0,11 €	0,12 €
Total cost per hour	11,36 €	11,89 €	12,42 €	12,96 €	13,49 €
System efficiency (%)	69 %	72 %	75 %	78 %	81 %
Total cost per hour	12,89 €	12,64 €	12,42 €	12,22 €	12,03 €

Figure 28: Sensitivity analysis of TCO of the 40 kW machinery using depot charging concept.

The depot charging concept allows for much greater uncertainty in the operation than the opportunity charging concept since the large battery allows longer operating duration. Decreasing the required operating duration to 8 hours from 16 hours also halves the battery's size and its cost. However, because of the reduced operating hours, the battery cost per hour stays the same.

Hybrid models of depot and opportunity charging concepts can also be created using exchangeable batteries. However, using an exchangeable battery after 8 hours to continue another 8 hours is not a viable option, because it would not effect the cost, since another expensive battery is needed. Bringing the operation model closer to that of the opportunity charging, using a 4-hour operating duration with 5,840 hours of yearly usage, would mean using two batteries, which are both 160 kWh in size, and the batteries are used and charged alternatively. Now the battery cost per hour is reduced by half, bringing the total cost per hour to 9.13 €, which is 3.29 € lower than the cost of the original depot charging concept. Trying different combinations of the different charging concepts presented here, a suitable hybrid solution can be found, that satisfeis the operating duration and total cost per hour requirements.

4.3 Limitations of the models

Key factors affecting TCO, cash flow, and profitability calculations of electrical and diesel machinery are difficult to estimate. Public data is difficult to find and some of the variables are based on results from interviews. Many of the variables depend on the size and layout of the harbor. This creates uncertainty in results. There are several factors listed below, that are not accounted for in the TCO calculations, or that are minor in comparison to other factors:

– Additional administrative costs, such as insurance, procurement etc. related to owning new electrical machinery

– Cost of additional charging equipment and batteries

– Cost of additional training

– Cost of backup generator and preparing for power outages

– Cost of externalities to the environment, such as reduced CO_2 tonnes

– Cost of machinery structure and motor

– Cost of maintenance for electrical machinery and charging equipment

– Cost of redimensioning transformers and relays

– Cost of reduced sick days

– Cost of refueling time

– Difference in cost of spare parts

– Difference in residual value

– Effect of driver, load, and machine design on power profile

– Effect of increased or decreased company reputation

– Effect of productivity in different scenarios

– Heating costs of charging equipment

– Government subsidies or tax reductions due to greener technology

– Machine availability and fault rate

– Savings generated from longer careers

– Uncertainty in diesel machinery comparison, and diesel price and consumption

The design of the harbor operations should be robust, which can create additional costs depending on the level of robustness. In order to minimize the risk of disturbances, more than one charging equipment should be installed to avoid faults, and a diesel backup generator should be prepared to minimize the effects of a power outage. In the TCOs presented in this thesis, the fleet relies on only one charging equipment. Due to the novelty of this equipment, there is no quarantee for 100% availability.

As discussed previously in chapter 2, the shuttle carrier does not need to wait for the STS crane as the carrier is able to lift a container, which means that in some operations there are no waiting periods between work cycles. In these sort of cases, other solutions have to be sought. One solution is that the charging could happen while the machine lifts the container or the battery is charged using technologies that allow the machinery to move simultaneously. In difficult cases, higher charging power and faster connection should be used.

In industrial environments, key factors such as availability, productivity, reliability, usability, utilization and efficiency, should be as high as possible, while other factors, such as fault frequency and maintenance time, should be as low as possible. These factors can be improved by proper operations design, simulations, and trial runs. [1, 59] In a best case scenario, the machinery electrification makes the refueling breaks unnecessary increasing utilization, productivity, and availability. For electrical machinery, there are less parts that need maintaining, but the cost of the service might be higher than the service for diesel machinery due the more technological and complex nature of electrical machinery and equipment.

High voltages and powers require more attention than the low voltages and powers used in electric cars. The level of danger rises with the amount of power that is transferred, which could mean that the charging equipment should be located out of reach otherwise personnel health could be compromised.

Using new type of machinery often requires employee training. The amount of necessary training could be minimized if the charging is made automatic, and there would be equipment to inform the driver about the state of charge (SoC), the duration of remaining drive time, and the required length of next charging period. Additional equipment could collect information about electricity consumption and battery capacity at different occasions. This would allow preparing for future renewal of equipment in advance. [41]

5 Conclusions

This thesis studied the prerequisite knowledge of implementing high power charging infrastructure and fully electrical machinery in harbor in environment. Prerequisite knowledge of implementing any new technology consists of defining whether the technology is feasible for the operating environment and financially profitable to use.

The reasons for studying the electrification of harbor machinery are manifold. Firstly, dependency on fossil fuels should be reduced. Secondly, implementing electrical machinery can bring several cost and environmental benefits. And thirdly, a contribution towards the electrification of industrial machinery wanted to be made.

For the thesis, two interviews were conducted. Using these interviews and other suitable sources, a comprehension of harbor operations and machinery could be formed. Based on this comprehension two generic models of operations could be built to study the technological feasibility of battery-operated machinery using opportunity and depot charging concepts. In this case, technological feasibility means whether the existing charging durations and powers together with current machinery and battery technology are enough to allow operation to run without disruptions or additional breaks. The operations models act as a basis for developing total cost of ownership models, which were compared to the TCO of a similar diesel machine. The models were analysed using sensitivity analysis to reveal critical factors in the models. These findings can be used to direct further study more accurately.

The baseline scenario for opportunity charging suggests that it can satisfy the requirements set by the operating environment, while being a competetitive alternative to using diesel machinery. The key factors found in the sensitivity analysis for this concept were: yearly usage, fleet size, and electricity price. The reason, why the charger cost is not a key factor, is that the cost is divided to the large fleet. The battery cost is not a key factor neither, because the size of the battery is small. All of the resulted hourly costs of the sensitivity analysis suggest that the concept is competitive to using diesel machinery. The most suitable machinery for electrification would be AGV, because they are usually used in large fleet size to compensate the lacking competence to lift containers. This results in waiting breaks, which can be utilized for oppotunity charging.

Currently, the depot charging concept does not seem to be able to compete with the opportunity charging concept in costs. Even the depot charging concept itself is not very competitive when compared to using diesel machinery, this is backed by the results of the sensitivity analysis. The reasons for high cost are high requirement for battery energy content, high unit cost of kWh, and short lifetime of battery. The costs of using the depot charging can be lowered by using exchangeable batteries.

The future of electrical machinery looks bright as they are already technoeconomically feasible to implement in harbor environments. The concepts and models developed here can also be applied to other industries as well. Industries such as forest and mining have traditionally used diesel and diesel-hybrid machines, that could be replaced with electric drives.

In order to form more precise estimates of the feasibility of machinery electrification in different harbors, more in-depth analyses of individual harbors has to be made. These analyses would cover such things as distance variations at the harbor, necessary average fleet size, power consumption of fleet, duration of breaks, cost of diesel and electricity, and required charging power and battery energy content. Additionally, technological aspects such as connecting and disconnecting times of the charging equipment should be studied, because they are critical in operations that have short breaks. Another worthwhile aspect to study further is the electrical braking and its influence on energy consumption, because energy costs make up majority of the TCO for opportunity charging. The cyclical operation is also suitable to fully benefit from electrical braking.

For the opportunity charging concept, the development of charging equipment should be done especially so that lower total costs are achieved. Currently, the technology is new, which makes the technical usage age short even though the actual lifetime would be longer. For the depot charging concept, reaching better energy densities, lower unit costs of kWh, and longer lifetime are imperative for the generalization of the technology. If battery develops far enough, it could offer similar flexibility to current diesel machinery.

References

[1] W. Jacobs, M.R. Hodkiewicz, and T. Bräunl. A cost-benefit analysis of electric loaders to reduce diesel emissions in underground hard rock mines. In *IEEE, Industry Applications Society Annual Meeting*, Vancouver, Canada, 2014.

[2] T. Karvonen and H. Tikkala. 2004. Satamatoimintojen kehittäminen ja satamia koskevan lainsäädännön uudistaminen. Publications of the Ministry of Transportation and Communications 65/2004. ISBN 952-201-211-4. [Web-document]. [Accessed 16.6.2015]. Available:. http://www.lvm.fi/fileserver/65_2004.pdf.

[3] K. Wallin. Satamien liikenteenohjauksen kehittäminen esimerkkinä Vuosaaren satama, Master's Thesis. Aalto University, Espoo, Finland, 2012.

[4] Harbor types. [Web-document]. Accessed: 29.4.2015. Available:. http://www.logistiikanmaailma.fi/wiki/Satamatyypit.

[5] J. Leskinen, Research and Development Engineer. Cargotec Oyj, Kalmar. Interview 12.6.2015. Ruskontie 55, 33720 Tampere, Finland.

[6] MEK-C3001 Kuljetusvälinetekniikka, course material, lecture 11, Espoo, Aalto University. https://noppa.aalto.fi/noppa/kurssi/mek-c3001/luennot/MEK-C3001_merikuljetukset.pdf.

[7] Dock operators. [Web-document]. Accessed: 29.4.2015. Available:. http://www.logistiikanmaailma.fi/wiki/Satama.

[8] P. Hellström, Development manager. Vuosaari Port. Komentosilta 1, 00980 Helsinki, Finland. Interview 18.6.2015.

[9] Water vessels. [Web-document]. Accessed: 29.4.2015. Available:. http://www.logistiikanmaailma.fi/wiki/Merikuljetukset_Suomessa.

[10] TU-91.2043 International economics, course material, lecture 1, Espoo, Aalto University.

[11] TU-91.2043 International economics, course material, lecture 3, Espoo, Aalto University.

[12] Water vessels. [Web-document]. Accessed: 29.4.2015. Available:. http://www.kuljetusopas.com/kalusto/vesiliikennekalusto/.

[13] STS crane. [Web-document]. Accessed: 29.4.2015. Available:. http://www.huadongzj.com/en/UploadFiles/20101129155623923.jpg.

[14] STS Schematics. [Web document]. Accessed: 29.4.2015. Available:. http://www.morrow.com/sites/default/files/images/products/container-gantry/STS-schematics.png.

[15] Terminal tractor. [Web-document]. Accessed: 29.4.2015. Available:. http://upload.wikimedia.org/wikipedia/commons/6/67/DHL_semi-trailer_-_unloaded_from_ferry.JPG.

[16] Automated guided vehicle. [Web-document]. Accessed: 29.4.2015. Available:. http://www.portstrategy.com/__data/assets/image/0008/673982/AGV_Rotterdam.jpg.

[17] Straddle. [Web document]. Accessed: 29.4.2015. Available:. http://www.konecranes.com/sites/default/files/gallery/straddle_carrier_final_low.jpg.

[18] Shuttle carrier. [Web-document]. Accessed: 29.4.2015. Available:. http://www.goodnewsfinland.com/Cargotec_Kalmar_Shuttle_Carrier.jpg.

[19] Konecranes shuttle brochure. [Web-document]. Accessed: 29.4.2015. Available:. http://www.konecranes.com/sites/default/files/download/konecranes_boxrunner_straddle_carrier_brochure_final.pdf.

[20] Cargotec shuttle carrier brochure. [Web-document]. Accessed: 29.4.2015. Available:. https://www.kalmarglobal.com/globalassets/equipment/shuttle-carriers/kalmar_shuttle_carrier_data_sheet.pdf.

[21] ASC. [Web document]. Accessed: 29.4.2015. Available:. http://www.konecranes.com/sites/default/files/gallery/asc_at_apm_terminals_portsmouth_usa.jpg.

[22] RTG crane. [Web-document]. Accessed: 29.4.2015. Available:. http://www.porttechnology.org/images/made/images/uploads/news/RTG_600_451.jpg.

[23] Reach stacker. [Web-document]. Accessed: 29.4.2015. Available:. http://www.hebezeuge-foerdermittel.de/sites/dev.hebezeuge-foerdermittel.de/files/bilder/Bild%201.jpg.

[24] Masted container handler. [Web-document]. Accessed: 29.4.2015. Available:. http://www.taylormachineworks.com/reach_stackers_files/THDC-T4.jpg.

[25] Forklift truck. [Web-document]. Accessed: 29.4.2015. Available:. http://img.directindustry.com/images_di/photo-g/sit-on-forklift-combustion-engine-handling-64449-7798687.jpg.

[26] L. Romana. Potential solutions for electric vehicles in bus and delivery traffic, Master's thesis. Aalto University, Department of Electrical Engineering, Espoo, Finland, 2010.

[27] L. Wilson. [web-document]. accessed: 7.9.2015. available:. http://shrinkthatfootprint.com/average-electricity-prices-kwh.

[28] Diesel prices. [web-document]. accessed: 7.9.2015. available:. http://www.globalpetrolprices.com/diesel_prices/.

[29] N. Nylund. Fuel savings for heavy duty vehicles "HDEnergy" summary report 2003-2005 [web-document]. Accessed: 14.7.2015. Available:. http://www.motiva.fi/files/1027/2006_HDEnergy_summaryreport_eng_final.pdf.

[30] DeepResource. [web-document]. Accessed: 14.7.2015. Available:. https://deepresource.wordpress.com/2012/04/23/energy-related-conversion-factors/.

[31] Next generation straddle and shuttle carriers. [Web-document]. Accessed: 14.7.2015. Available:. http://ecv-fi-bin.directo.fi/@Bin/12719dd882463f8a0a32cafe50b95058/1436879892/application/pdf/210156/Leskinen_Hybrid_presentation_public.pdf.

[32] Kalmar hybrid straddle carrier sets new standard for fuel consumption and Belgium. [Web-document]. Accessed: 14.7.2015. Available: emissions at MSC Home Terminal in Antwerp. https://www.kalmarglobal.com/newsroom/press_releases/2014/kalmar-hybrid-straddle-carrier-sets-new-standard-for-fuel-consumption-and-emissions-at-msc-home-terminal-in-antwerp-belgium/.

[33] Dieselnet.com. [Web document]. Accessed: 14.7.2015. Available:. https://www.dieselnet.com/standards/us/nonroad.php.

[34] Dieselnet.com. [Web document]. Accessed: 14.7.2015. Available:. https://www.dieselnet.com/standards/eu/nonroad.php#s5.

[35] M. Schipper and K. Perl. Tier standards. u.s. energy information administration. [web-document]. accessed: 14.7.2015. available:. http://www.eia.gov/todayinenergy/detail.cfm?id=18151.

[36] S. Vaurio. Litiumioniakun oikosulkusuojaus hybridityökoneessa, Master's thesis. Aalto University, Espoo, Finland, 2013.

[37] S. Kukkonen. Research scientist. Personal communication. VTT Technical Research Centre of Finland, Espoo, Finland, 2015.

[38] I. Alhonsalo. Litiumakkujen syklitestausjärjestelmä, Master's thesis. Tampere University of Technology, Tampere, Finland, 2012.

[39] Battery university. [Web-document]. Accessed: 9.7.2015. Available:. http://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries.

[40] H. Lehtinen. Sähköbussit osana Turun seudun joukkoliikennejärjestelmää, Master's Thesis, Tampere University of Technology, Tampere, Finland 2014.

[41] S. Kukkonen and A. Lehtinen. ECV-eCharge – käyttöympäristöjen vaatimukset sekä käyttökonseptien määrittely. [VTT internal document]. Accessed: 6.7.2015. VTT Technical Research Center of Finland. Espoo, Finland, 2014.

[42] B. Nykvist and M. Nilsson. Rapidly falling costs of battery packs for electric vehicles. In *Letter Nature climate change*, Stockholm, Sweden, 2015.

[43] Ü. Yurdakul. Sähköautojen latausverkon yleissuunnittelu, Master's thesis. Aalto University, Department of Electrical Engineering, Espoo, Finland, 2013.

[44] V. Tikka. Sähköautojen pikalatauksen verkkovaikutukset, Master's thesis. Lappeenranta University of Technology, Department of Technology, Lappeenranta, Finland, 2010.

[45] Charging standards. [VTT internal document]. Accessed: 29.4.2015.

[46] Offboard charging. [Web-document]. Accessed: 29.4.2015. Available:. http://www.siemens.com/press/pool/de/pressebilder/2014/mobility/300dpi/IM2014110115MO_300dpi.jpg.

[47] CleanCityAlliance. [Web document]. Accessed: 19.7.2015. Available:. http://cleancityalliance.nl/.

[48] Heliox. [Web document]. Accessed: 19.7.2015. Available:. http://heliox.nl/wp-content/uploads/2014/06/Heliox-Fast-Opportunity-Charge-120kW-200kW-500kW.pdf.

[49] Hilma. Suorahankintaa koskeva ilmoitus: Espoon kaupunki: Sähköbussien automaattinen latauslaite. [web-document]. Accessed: 13.9.2015. Available:. http://www.hankintailmoitukset.fi/fi/notice/view/2015-013222/.

[50] Electric cars report. Volvo completes study of wireless charging. [web-document]. accessed: 14.9.2015. available:. http://electriccarsreport.com/2013/10/volvo-completes-study-wireless-charging/.

[51] J. Markkula. Sähköautojen latauspalvelut ja latausliiketoiminta, Master's thesis. Tampere University of Technology, Department of Electrical Engineering, Tampere, Finland, 2013.

[52] Overhead line. [Web-document]. Accessed: 29.4.2015. Available:. http://www.distritomotor.com/DMS-Imagenes/Imagenes/SIEMENS/SIEMENS_eHighway/SIEMENS_eHighway_8.jpg.

[53] K. Sandberg. Jarrutusenergian talteenotto helsingin metro- ja raitioliikenteessä, Master's thesis. Aalto University, Department of Electrical Engineering, Espoo, Finland, 2015.

[54] J. Wan, Q. Meng, and W. Wang. Optimization for container handling equipments allocation based on ARENA. In *IEEE 17th International Conference on Industrial Engineering and Engineering Management*, 2010.

[55] B. Xu and J. He. Tabu search for container dock handling scheduling. In *International Conference on Management and Service Science*, 2009.

[56] S. Hoshino and J. Ota. Performance design of operating robots in a seaport container-handling system. In *IEEE Conference on Automation Science and Engineering*, Scottsdale, USA, 2007.

[57] Byung-Hyun Ha, Eun-Jung Park, and Chan-Hee Lee. A simulation model with a low level of detail for container terminals and its applications. In *Simulation Conference*, Washington DC, USA, 2007.

[58] Konecranes reach stacker brochure. [Web-document]. Accessed: 12.8.2015. Available:. http://www.konecranes.com/sites/default/files/download/kc_rst_print_8809022_low.pdf.

[59] G.M. Valenzuela and M.A. Valenzuela. Integrated mechanical-electrical modeling of an AC electric mining shovel and evaluation of power requirements during a truck loading cycle. In *IEEE Industry Applications Society Annual Meeting*, 2014.

A Sensitivity analysis

This section presents the TCO sensitivity analyses for opportunity and depot charging concepts. The studied machinery are 20, 60, and 80 kW.

A.1 Opportunity charging concept

To study the sensitivity of variable changes, each variable is changed at a time, while a range of values is assigned to the studied variable. The baseline values are the same as in chapter 4.2.1. However, in figures A1, A2, and A3, the sensitivity of TCOs is studied, assuming in the baseline case, that there is enough battery energy content to operate the machineries for a maximum of 1 hour. This translates to battery sizes of 20, 60, and 80 kWh for the 20, 60, and 80 kW machines, respectively. Increasing machinery power by 20 kW raises TCOs of the baseline cases around 2,50 €. As power increases, the effect of electricity price and system efficiency becomes more greater.

Yearly usage (h)	2920	4380	5840	7300	8760
Total cost per hour	4,68 €	3,88 €	3,48 €	3,24 €	3,08 €
Battery size (kWh)	10	20	30	40	50
Total cost per hour	3,03 €	3,48 €	3,77 €	4,00 €	4,21 €
Fleet size	2	3	4	5	6
Total cost per hour	4,77 €	4,06 €	3,70 €	3,48 €	3,34 €
Unit cost of kWh (€)	400	600	800	1000	1200
Total cost per hour	3,28 €	3,35 €	3,42 €	3,48 €	3,55 €
Charger cost (€)	150 000 €	200 000 €	250 000 €	300 000 €	350 000 €
Total cost per hour	3,14 €	3,31 €	3,48 €	3,66 €	3,83 €
Charger lifetime (years)	6	8	10	12	14
Total cost per hour	4,06 €	3,70 €	3,48 €	3,34 €	3,24 €
Battery lifetime (years)	6	8	10	12	14
Total cost per hour	3,71 €	3,57 €	3,48 €	3,43 €	3,39 €
Electricity price (€/kWh)	0,08 €	0,09 €	0,10 €	0,11 €	0,12 €
Total cost per hour	3,03 €	3,26 €	3,48 €	3,71 €	3,94 €
System efficiency (%)	69 %	72 %	75 %	78 %	81 %
Total cost per hour	3,68 €	3,58 €	3,48 €	3,40 €	3,32 €

Figure A1: Sensitivity analysis of TCO for the 20 kW machinery using opportunity charging concept.

Yearly usage (h)	2920	4380	5840	7300	8760
Total cost per hour	10,62 €	9,37 €	8,74 €	8,36 €	8,11 €
Battery size (kWh)	40	50	60	70	80
Total cost per hour	7,94 €	8,38 €	8,74 €	9,05 €	9,34 €
Fleet size	2	3	4	5	6
Total cost per hour	10,02 €	9,31 €	8,95 €	8,74 €	8,60 €
Unit cost of kWh (€)	400	600	800	1000	1200
Total cost per hour	8,12 €	8,33 €	8,54 €	8,74 €	8,95 €
Charger cost (€)	150 000 €	200 000 €	250 000 €	300 000 €	350 000 €
Total cost per hour	8,40 €	8,57 €	8,74 €	8,91 €	9,08 €
Charger lifetime (years)	6	8	10	12	14
Total cost per hour	9,31 €	8,95 €	8,74 €	8,60 €	8,50 €
Battery lifetime (years)	6	8	10	12	14
Total cost per hour	9,43 €	9,00 €	8,74 €	8,57 €	8,45 €
Electricity price (€/kWh)	0,08 €	0,09 €	0,10 €	0,11 €	0,12 €
Total cost per hour	7,37 €	8,05 €	8,74 €	9,43 €	10,11 €
System efficiency (%)	69 %	72 %	75 %	78 %	81 %
Total cost per hour	9,34 €	9,03 €	8,74 €	8,48 €	8,23 €

Figure A2: Sensitivity analysis of TCO for the 60 kW machinery using opportunity charging concept.

Yearly usage (h)	2920	4380	5840	7300	8760
Total cost per hour	13,59 €	12,11 €	11,37 €	10,92 €	10,63 €
Battery size (kWh)	60	70	80	90	100
Total cost per hour	10,61 €	11,01 €	11,37 €	11,59 €	11,76 €
Fleet size	2	3	4	5	6
Total cost per hour	12,65 €	11,94 €	11,58 €	11,37 €	11,23 €
Unit cost of kWh (€)	400	600	800	1000	1200
Total cost per hour	10,55 €	10,82 €	11,09 €	11,37 €	11,64 €
Charger cost (€)	150 000 €	200 000 €	250 000 €	300 000 €	350 000 €
Total cost per hour	11,03 €	11,20 €	11,37 €	11,54 €	11,71 €
Charger lifetime (years)	6	8	10	12	14
Total cost per hour	11,94 €	11,58 €	11,37 €	11,23 €	11,12 €
Battery lifetime (years)	6	8	10	12	14
Total cost per hour	12,28 €	11,71 €	11,37 €	11,14 €	10,98 €
Electricity price (€/kWh)	0,08 €	0,09 €	0,10 €	0,11 €	0,12 €
Total cost per hour	9,54 €	10,45 €	11,37 €	12,28 €	13,20 €
System efficiency (%)	69 %	72 %	75 %	78 %	81 %
Total cost per hour	12,16 €	11,75 €	11,37 €	11,02 €	10,69 €

Figure A3: Sensitivity analysis of TCO for the 80 kW machinery using opportunity charging concept.

A.2 Depot charging concept

The analyses for the sensitivity of TCO for depot charging assume, that the baseline values are the same as in chapter 4.2.2. However, all of the machines should be able to operate 16 hours in order to be comparable, which means that the baseline values for battery energy content are 320, 960, and 1280 kWh for the 20, 60, and 80 kW machinery, respectively. The analyses are presented in figures A4, A5, A6. The baseline TCOs increase around 6.00 € everytime machinery power is increased by 20 kW. Similar to the opportunity charging concept, the importance of electricity price and system efficiency increases when power increases.

Yearly usage (h)	2920	4380	5840	7300	8760
Total cost per hour	6,98 €	6,64 €	6,47 €	6,37 €	6,30 €
Unit cost of kWh (€/kWh)	200	400	600	800	1000
Total cost per hour	4,28 €	5,37 €	6,47 €	7,56 €	8,66 €
Fleet size	1	2	3	4	5
Total cost per hour	6,47 €	6,47 €	6,47 €	6,47 €	6,47 €
Charger cost (€)	10 000 €	20 000 €	30 000 €	40 000 €	50 000 €
Total cost per hour	6,13 €	6,30 €	6,47 €	6,64 €	6,81 €
Charger lifetime (years)	6	8	10	12	14
Total cost per hour	6,81 €	6,60 €	6,47 €	6,38 €	6,32 €
Battery lifetime (years)	6	8	10	12	14
Total cost per hour	8,66 €	7,29 €	6,47 €	5,92 €	5,53 €
Electricity price (€/kWh)	0,08 €	0,09 €	0,10 €	0,11 €	0,12 €
Total cost per hour	5,93 €	6,20 €	6,47 €	6,73 €	7,00 €
System efficiency (%)	69 %	72 %	75 %	78 %	81 %
Total cost per hour	6,70 €	6,58 €	6,47 €	6,37 €	6,27 €

Figure A4: Sensitivity analysis of TCO for the 20 kW machinery using depot charging concept.

Yearly usage (h)	2920	4380	5840	7300	8760
Total cost per hour	18,89 €	18,55 €	18,38 €	18,27 €	18,21 €
Unit cost of kWh (€/kWh)	200	400	600	800	1000
Total cost per hour	11,80 €	15,09 €	18,38 €	21,66 €	24,95 €
Fleet size	1	2	3	4	5
Total cost per hour	18,38 €	18,38 €	18,38 €	18,38 €	18,38 €
Charger cost (€)	10 000 €	20 000 €	30 000 €	40 000 €	50 000 €
Total cost per hour	18,03 €	18,21 €	18,38 €	18,55 €	18,72 €
Charger lifetime (years)	6	8	10	12	14
Total cost per hour	18,72 €	18,51 €	18,38 €	18,29 €	18,23 €
Battery lifetime (years)	6	8	10	12	14
Total cost per hour	24,95 €	20,84 €	18,38 €	16,73 €	15,56 €
Electricity price (€/kWh)	0,08 €	0,09 €	0,10 €	0,11 €	0,12 €
Total cost per hour	16,78 €	17,58 €	18,38 €	19,18 €	19,98 €
System efficiency (%)	69 %	72 %	75 %	78 %	81 %
Total cost per hour	19,07 €	18,71 €	18,38 €	18,07 €	17,78 €

Figure A5: Sensitivity analysis of TCO for the 60 kW machinery using depot charging concept.

Yearly usage (h)	2920	4380	5840	7300	8760
Total cost per hour	24,84 €	24,50 €	24,33 €	24,23 €	24,16 €
Unit cost of kWh (€/kWh)	200	400	600	800	1000
Total cost per hour	15,56 €	19,95 €	24,33 €	28,71 €	33,10 €
Fleet size	1	2	3	4	5
Total cost per hour	24,33 €	24,33 €	24,33 €	24,33 €	24,33 €
Charger cost (€)	10 000 €	20 000 €	30 000 €	40 000 €	50 000 €
Total cost per hour	23,99 €	24,16 €	24,33 €	24,50 €	24,67 €
Charger lifetime (years)	6	8	10	12	14
Total cost per hour	24,67 €	24,46 €	24,33 €	24,25 €	24,18 €
Battery lifetime (years)	6	8	10	12	14
Total cost per hour	33,10 €	27,62 €	24,33 €	22,14 €	20,57 €
Electricity price (€/kWh)	0,08 €	0,09 €	0,10 €	0,11 €	0,12 €
Total cost per hour	22,20 €	23,26 €	24,33 €	25,40 €	26,46 €
System efficiency (%)	69 %	72 %	75 %	78 %	81 %
Total cost per hour	25,26 €	24,78 €	24,33 €	23,92 €	23,54 €

Figure A6: Sensitivity analysis of TCO for the 80 kW machinery using depot charging concept.

B Cash flow and profitability analysis

The cash flow analysis consists of the initial investment cost and future cash flows, that are discounted to present value (PV) using a discount factor (DF) to calculate a net present value (NPV). A positive NPV is considered a good investment, because it exceeds the required return i. The general formula for NPV is presented here:

$$\text{NPV} = \sum_{t=0}^{N} \frac{\text{Cash flow}_t}{(1+i)^t}, \tag{B1}$$

where t denotes the year the cash flow occurs and i denotes the interest rate.

B.1 Opportunity charging concept

For the opportunity charging base case, the yearly savings are 275,314 €, while the initial investment costs for the opportunity charging concept are:

$$\text{Initial investment} = \text{Charger cost} + \text{Fleet size} \cdot \text{Battery cost}, \tag{B2}$$

which totals to 450,000 €, if 40 kWh batteries are used and the fleet size is 5 vehicles. The cash flows and discount factors are presented in table B1 using a 10% discount rate.

Table B1: NPV calculation for 40 kW machinery using the opportunity charging concept

Year	**Cash flow**	**DF**	**PV**
0	–450,000 €	1.0000	–450,000 €
1	275,314 €	0.9091	250,286 €
2	275,314 €	0.8264	227,532 €
3	275,314 €	0.7513	206,848 €
4	275,314 €	0.6830	188,043 €
5	275,314 €	0.6209	170,949 €
6	275,314 €	0.5645	155,408 €
7	275,314 €	0.5132	141,280 €
8	275,314 €	0.4665	128,436 €
9	275,314 €	0.4241	116,760 €
10	275,314 €	0.3855	106,146 €
NPV			**1,241,687 €**

A positive NPV of 1,241,687 € is a profitable investment. Other metrics such as the internal rate of return (IRR) and payback time resulted in 61% and 1.6 years, respectively. This means that the investment in electrical machinery will cover the initial investment costs quickly. The calculations change when other costs such as the rest of the machine structure is included.

Performing sensitivity analysis on the NPV calculations, figure B1 shows the sensitivity of hourly savings, if the costs of electricity and diesel are changed. Operating

	Diesel				
Electricity	**10,00 €**	**12,00 €**	**14,00 €**	**16,00 €**	**18,00 €**
3,00 €	7,00 €	9,00 €	11,00 €	13,00 €	15,00 €
4,00 €	6,00 €	8,00 €	10,00 €	12,00 €	14,00 €
5,00 €	5,00 €	7,00 €	9,00 €	11,00 €	13,00 €
6,00 €	4,00 €	6,00 €	8,00 €	10,00 €	12,00 €
7,00 €	3,00 €	5,00 €	7,00 €	9,00 €	11,00 €

Figure B1: Sensitivity analysis of hourly savings.

5 vehicles 5,840 hours per year, the sensitivity of yearly savings are presented in figure B2. Now the sensitivity of NPV can be analyzed, if the initial investment costs

Yearly savings				
204 400,00 €	262 800,00 €	321 200,00 €	379 600,00 €	438 000,00 €
175 200,00 €	233 600,00 €	292 000,00 €	350 400,00 €	408 800,00 €
146 000,00 €	204 400,00 €	262 800,00 €	321 200,00 €	379 600,00 €
116 800,00 €	175 200,00 €	233 600,00 €	292 000,00 €	350 400,00 €
87 600,00 €	146 000,00 €	204 400,00 €	262 800,00 €	321 200,00 €

Figure B2: Sensitivity analysis of yealy savings.

are changed. NPV sensitivity for initial investment costs of 300,000 €, 450,000 €, and 600,000 € are presented in figure B3. The used discount rate is 10% and holding period 10 years. From the figure it can be seen, that the NPV stays positive for almost all of the scenarios. Only when the hourly savings are at minimum (3.00 €) and the initial investment cost is highest at 600,00 €, the NPV becomes negative.

300,000€ Initial investment				
955 949,52 €	1 314 792,24 €	1 673 634,95 €	2 032 477,67 €	2 391 320,39 €
776 528,16 €	1 135 370,88 €	1 494 213,59 €	1 853 056,31 €	2 211 899,03 €
597 106,80 €	955 949,52 €	1 314 792,24 €	1 673 634,95 €	2 032 477,67 €
417 685,44 €	776 528,16 €	1 135 370,88 €	1 494 213,59 €	1 853 056,31 €
238 264,08 €	597 106,80 €	955 949,52 €	1 314 792,24 €	1 673 634,95 €
450,000€ Initial investment				
805 949,52 €	1 164 792,24 €	1 523 634,95 €	1 882 477,67 €	2 241 320,39 €
626 528,16 €	985 370,88 €	1 344 213,59 €	1 703 056,31 €	2 061 899,03 €
447 106,80 €	805 949,52 €	1 164 792,24 €	1 523 634,95 €	1 882 477,67 €
267 685,44 €	626 528,16 €	985 370,88 €	1 344 213,59 €	1 703 056,31 €
88 264,08 €	447 106,80 €	805 949,52 €	1 164 792,24 €	1 523 634,95 €
600,000€ Initial investment				
655 949,52 €	1 014 792,24 €	1 373 634,95 €	1 732 477,67 €	2 091 320,39 €
476 528,16 €	835 370,88 €	1 194 213,59 €	1 553 056,31 €	1 911 899,03 €
297 106,80 €	655 949,52 €	1 014 792,24 €	1 373 634,95 €	1 732 477,67 €
117 685,44 €	476 528,16 €	835 370,88 €	1 194 213,59 €	1 553 056,31 €
- 61 735,92 €	297 106,80 €	655 949,52 €	1 014 792,24 €	1 373 634,95 €

Figure B3: Sensitivity analysis of NPV for different initial investment costs.

B.2 Depot charging concept

The initial investment costs for the depot charging concept are:

$$\text{Initial investment} = \text{Fleet size} \cdot \text{Charger cost} + \text{Fleet size} \cdot \text{Battery cost}, \tag{B3}$$

since each vehicle needs a charger. The initial investment costs total to 414,000 €, while the yearly cost savings are only 50,613 €. The resulting NPV from 10 years is –103,003 €. Table B2 presents the NPV calculations for the depot charging concept. Payback time and IRR are not relevant in this case, because the great negative NPV already shows that the depot charging concept is not a worthwhile investment opportunity. For the investment to be profitable, the price of electricity would have to be about 0.046 €/kWh, if other variables are kept constant.

Table B2: NPV calculations for 40 kW machinery using the depot charging concept

Year	**Cash flow**	**DF**	**PV**
0	–414,000 €	1.0000	–414,000 €
1	50,613 €	0.9091	46,012 €
2	50,613 €	0.8264	41,829 €
3	50,613 €	0.7513	38,027 €
4	50,613 €	0.6830	34,570 €
5	50,613 €	0.6209	31,427 €
6	50,613 €	0.5645	28,570 €
7	50,613 €	0.5132	25,973 €
8	50,613 €	0.4665	23,611 €
9	50,613 €	0.4241	21,465 €
10	50,613 €	0.3855	19,514 €
NPV			**–103,003 €**